Time-symmetric Quantum Mechanics in the Block Universe

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A thesis presented for the degree of
MSc History and Philosophy of Science

Universiteit Utrecht

Faculty of Science
Utrecht University
8th October, 2021

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Scientific summary

The present thesis addresses a general and a specific research question. The general research question aims to explore whether the block universe perspective provides a smooth reconciliation between quantum mechanics and special relativity. The specific question is whether time-symmetric quantum mechanics requires retrocausality, action-at-a-temporal-distance, or mere temporal global correlations.

We assume a definition of the block universe perspective that requires fundamental time symmetry, so we ask whether time-symmetric quantum mechanics has properties that enable a local explanation for the violation of spacelike Bell inequalities. In this context, we analyse the retrocausal argument proposed by Price (2012) and the subsequent theorem advanced by Leifer and Pusey (2017). These arguments maintain that, under certain assumptions, time-symmetric quantum mechanics requires retrocausality. A crucial element is that retrocausality takes the form of a violation of the measurement independence condition. Such a violation enables a local explanation for the results of Bell's theorem. Therefore, if the block universe requires time-symmetry, a quantum theory compatible with this metaphysical perspective would be locally explained.

Nevertheless, there is another interpretation of what time-symmetric quantum theory entails, which is due to Adlam (2018b). She claims that Leifer and Pusey's theorem should be interpreted as involving temporal non-locality. Moreover, she argues that a temporally non-local theory implies action-at-a-temporal distance.

In this context, we offer a third interpretation of the retrocausality arguments, which maintains that time-symmetric quantum mechanics might require mere temporal global correlations. Temporal global correlations are non-local, but they do not require action-at-a-distance. Our argument is analogous to the interpretation developed by Myrvold (2016) for the spacelike case; while the violations of parameter independence imply action-at-a-distance, the violations of outcome independence exhibit mere global correlations. In the timelike case, unlike retrocausality or action-at-a-temporal-distance, temporal global correlations do not violate measurement independence, but (timelike) outcome independence. We reinforce our argument through an analysis of time-symmetric collapse models, a recent interpretation of dynamical collapse theories developed by Bedingham and Maroney (2017a).

We conclude that whether quantum mechanics in the block universe provides a reconciliation with special relativity is an open question. On one hand, if time-symmetric quantum theories require retrocausality or action-at-a-temporal distance à la Adlam, then the block universe does reconcile quantum mechanics with special relativity. On the other, if time-symmetric quantum mechanics exhibits mere temporal global correlations, then it does not give us means to explain spacelike non-locality.

Acknowledgements

The present master's thesis is my introductory research to the philosophy of physics in general, and the philosophy of quantum mechanics in particular. I started to study these topics about two years ago when I enrolled in the History and Philosophy of Science programme. In these years, and especially while I was writing this thesis, I have been taught, guided, and helped by several people, to whom I owe so much.

I am deeply grateful to Ronnie Hermens, the daily (and first) supervisor of this thesis, for his engagement and commitment to this research project. He was present in all the stages of this thesis, and he gave me extensive and detailed feedback on different versions of it. I have learned so much from his comments and our discussions, from conceptual points on quantum mechanics, writing style, improving argumentation skills, new philosophical tools of the field, to some strategies about how to use LaTeX. His criticism has always been friendly and fruitful.

I also have the honour of expressing my gratitude to Guido Bacciagaluppi, who is also the first supervisor of this thesis, for his guidance, availability, and kindness. I am very grateful for his fructiferous critical comments, and the exciting discussions we had on the topics of this thesis. We had several meetings that gave shape to the arguments of the present research. He taught (with Ronnie) the first course I attended in philosophy of quantum mechanics, where I had my first approximation to quantum theory.

I thank Fred Muller for agreeing to be the second supervisor of this thesis. I shall also mention the philosophy of physics research seminar, organised by him, which has played a central role in my introduction to the field.

I would like to show my gratitude to my HPS friends, with whom I had large conversations and discussions about the topics present in this thesis, and so many others. I shall mention particularly, Samar Khan, Mon Klein, Giulio Pandolfi, Fleur Petit, and Edoardo Tagliani. I would like to thank especially Fleur for her feedback and help with resolving my incompetence with LaTeX.

I do not have words to thanks Constanza Gonzalez, my partner in this adventure, for her support and love. Without her, it is difficult to see how I would have even started this thesis and survived the COVID-19 pandemic.

Finally, I shall mention my family, and especially my mother, who always motivated and supported me to pursue my passion for philosophy. I also dedicate this thesis to Jean Louis Warnier (1935-2021), my grandfather, who emigrated from France to Chile, to end up growing lavenders in the Elqui Valley, and without whom I would have never been able to continue my studies in Europe.

Contents

1 Introduction

In 1935, Schrödinger stated that entanglement was the feature that distinguishes the quantum from the classical domain. When two systems are entangled, they do not have their individual states. Earlier that year, Einstein, Podolsky and Rosen showed, using a thought experiment concerning two entangled systems measured at different laboratories, that quantum mechanics needed a completion since in its current state it was non-local. Almost 30 years later, in 1964, Bell articulated his first proof that quantum mechanics, even if after a putative completion, must involve non-locality.

The problem of non-locality is intrinsically related to the so-called quantum measurement problem. The measurement problem consists in explaining why our description of the quantum world which involves objects in a superposition between different states, does not match what we see in the macroscopic world with which we interact. This puzzle was illustrated by Schrödinger in 1935 as well by his famous thought experiment about a cat which is in a superposition of being alive and dead.

87 years after these formulations of the two mentioned puzzles, there is still no agreement about how to solve them. Of course, there has been advances and changes in the debates over the years, although the core of them remain the same.

The puzzle this thesis aims to face is how the non-locality implied by putative solutions to the measurement problem might be reconciled with the dynamical constraints imposed by special relativity. We are concerned with how an explanation of why measurements have definite results imply that two entangled systems will give correlated outcomes no matter how far away from each other they are. Relative to different solutions of the measurement problem, non-locality is understood differently. The clearest illustration of the problem with relativity is that in some accounts, joint measurements of entangled systems involve what Einstein called 'spooky-action-at-a-distance', that is, influences that should entail a mediation travelling faster than the velocity of light, which is prohibited by special relativity.

The puzzle of non-locality in quantum mechanics, and its apparent incompatibility with special relativity, has been studied from different points of view. Nevertheless, none of them has *explicitly* considered the block universe perspective as a possible *straightforward* solution. The general research question of this thesis aims to fill this gap. It is true that some proposals seem to require, or at least fit very well with, the block universe perspective, as it is the case of Price's retrocausality. However, the role that the block universe perspective can play might be different, and this has never been directly addressed. In this thesis, we will assume that the block universe requires time symmetry. The available literature has identified that time-symmetric quantum mechanics involve either retrocausality or action-at-a-temporal-distance. In this thesis, we offer a third alternative, according to which some time-symmetric quantum theories exhibit temporal global correlations, that is, dependencies at the statistical level that cannot be explained by common causes. The specific research addresses this demand: if the block universe requires time symmetry, then does the block universe require retrocausality, action-at-a-temporal-distance, or temporal global correlations?

In short, this thesis is an attempt to contribute to the understanding of non-locality in quantum mechanics by an analysis of what are the implications of time-symmetric quantum theories in the block universe. Before giving a more detailed description of the general and specific research questions, let us introduce some relevant concepts. In this thesis, we shall assume some familiarity with quantum mechanics. To achieve it, we redirect the reader to (Susskind and Friedman, 2014), (Ismael, 2021), and (Myrvold, 2018).

The block universe perspective. The block universe is a metaphysical hypothesis about the nature of fundamental events in spacetime, which maintains that the past and the future are ontologically equivalent at the fundamental level. In this view, past events and future events are on a pair; there is no property, nor physical law that enables a qualitative distinction between them.

Dainton (2016, p. 11) defines the block universe perspective as follows: "the block view: all times and events timelessly coexist, and all are equally real; temporal passage is unreal." In this thesis, we shall employ this definition of the block universe. This does not mean that everyone will agree with it. We believe that how the block universe is defined depends on which are the arguments by means it is defended.

There are two main argumentative lines to argue in favour of the block universe. The first one comes from an interpretation of special relativity. A consequence of the principle of relativity and the light postulate is that there is no absolute simultaneity. This is often understood as the impossibility to define an absolute present, and thus, ascribe it a special property, that distinguishes it from the past and the future (see (Saunders, 2002)).

The second one is based on the dynamical time symmetry of the fundamental laws of physics. The key idea is that if the laws of physics at the fundamental level are time-symmetric in the strict sense that the world would look the same if time is running from the initial state of the universe towards the final state, or from the final state to the initial state, we do not have any means to posit a distinction between past and future. Given our specific purposes, in this thesis, we shall focus only on this argumentative line.

Dainton (2016, p. 44) captures the essence of the dynamical argument to defend the block universe perspective: "if time really did flow, then, like a flowing river, it would also have a direction." By modus tollens, if there is no direction, then there cannot be flow. If we look at the fundamental laws of physics, we will not find any means to pick out such a preferred direction. Insisting in a direction would be analogous to stand firm to the belief that there is an absolute space, after the articulation of Galilean space-time.

The dynamical argument is reinforced if we assume McTaggart's metaphysics of time. According to McTaggart (1908), events in time can be divided into three different ways; 'A-series', 'B-series, and 'C-series'. The 'A-series' sort events on time in terms of *past*, *present* and *future*. If the 'A-series' represent something real, which would mean that there are absolute features that individuate pastness, presentness and futurity, then there is an absolute flow of time, independent of any conscious being. The 'B-series' divide events in '*earlier than*', and '*later than*', in such a way that there is an asymmetry between the events. Roughly, if the first case of COVID-19 was detected earlier than the creation of the first RNA vaccine that stimulates an immune response to the virus, the former is related to the latter in a temporally asymmetric way. If the former took place earlier than the latter, this will remain as a *permanent relation*, independent of any temporal perspective. Although the 'B-series' entail a temporal asymmetry, they do not involve an objective temporal passage. Finally, the 'C-series' distribute events in terms of *temporal betweenness*. This means that events are ordered, but not in a temporal way. Thus, these series do not involve either temporal asymmetry, or temporal passage, but rather mere intervals between events.

Without entering into details, the crucial part of McTaggart's argument for the purposes of this thesis is that the 'B-series' can only represent something real if the 'A-series' are real as well. As a result, according to McTaggart (1908), events can be ordered in a time-asymmetric way if and only if there is a flow of time, and we are entitled to ascribe them properties related to *pastness*, *presentness* and *futurity*. However, if the 'A-series' illustrate the fundamental characteristics of events, then they are evidence against the block universe perspective since they provide clear means to distinguish the past from the future, as well as a special property of *presentness*. In this case, it would not be possible to claim that insisting on a preferred time orientation is analogue to hold on to absolute space.

In consequence, assuming McTaggart's argument, the block universe requires the 'C-series', that is, time symmetry. In this view, the dynamical laws of physics cannot pick out a preferred time-orientation at the fundamental level. Relations of '*earlier than*' and '*later than*', as well as past, present, and future, are emergent, and they depend on a temporal perspective.

Consequently, if we aim to study the block universe from a metaphysically naturalised perspective, then we need to study the characteristics of dynamically time-symmetric physical laws.

Price (1996) argued that, when we adopt the atemporal perspective that the block universe enables, we should be careful of not falling into a fallacy of temporal double standards. To prevent this, we shall consider Price's guard against temporal double standards, as a principle, which we shall call Price's principle of no temporal double standards. Following (Price, 1996, p. 48), we define the principle as follows: "[we cannot accept] arguments with respect to one temporal direction which we wouldn't accept with respect to the other. Double standards need to be justified, and since a justification has to provide a reason for treating the past and the future differently, it is bound to embody or rely on some further principle of temporal asymmetry." This provides an important guide for our research, and we shall come back to it during our analysis.

Some caveats are important. In the block universe view, relations of *earlier than* and *later than*, as well as *past*, *present* and *future* are emergent and/or depend on a temporal perspective. It is not claimed that there are no temporal asymmetries or arrows of time. However, in this view, those asymmetries need to be *explained*. Usually, those explanations are given in terms of asymmetric boundary conditions, which are associated with emergent phenomena. This is the case with the thermodynamic arrow of time, which needs special initial conditions. In other cases, the asymmetries are explained in terms of conventions, which sometimes are closely associated with an epistemic asymmetry (agents know of events in their past but not about events in their future) (see (Price, 1996)).

Finally, it should be noticed the block universe perspective does not imply determinism. The ontological claim that past and future events are equally real is logically different from the question about how those events are dynamically related. As Sklar (1976, p. 273) puts it: "this is not, of course, to deny the importance of whether the universe is deterministic, but that issue is an issue about the relations future events bear to present and past events, not about the determinate reality of future events." Thus, the block universe should not be taken as implying determinism, and indeterminism should not be considered as a case against the block universe perspective.

Time symmetry. The dynamical symmetries of the laws of physics have played a very important role in the development and understanding of contemporary physics (see (Brading et al., 2021)). The following considerations follow (Sklar, 1976). Many of the most important symmetries are related to the structure of spacetime. For example, there is the invariance under spatial translation, invariance under temporal translation, invariance under spatial rotation, invariance under change of inertial frame, and invariance under spatial reflection. This thesis focuses on time symmetry, which is the product of time-reversal invariance.

Some remarks about dynamical symmetries would help us to understand time symmetry. There are *active* and *passive* interpretations of the dynamical symmetries. Let's take spatial translation as an illustration. In a deterministic scenario, an *active* interpretation of such a transformation considers that the phenomenon will evolve from the same initial state to the same final state, passing by the same intermediary states, disregarding whether a spatial translation transformation is performed or not. Simply put, the phenomenon (itself) is left invariant under a spatial translation. In an indeterministic scenario (as it is the quantum mechanical case), what would be left invariant under spatial translation would be the transition probabilities between the various possible states.

A *passive* interpretation of spatial translation concerns the *invariance of a description* after a spatial translation transformation. For example, a given phenomenon can be described from two different perspectives, that is, from two different positions in space. The initial and final state of the two descriptions are different since they are relative to a spatial perspective, *but* given the symmetry of spatial translation, the *laws* that describe the phenomenon would be the same from both perspectives. In other words, a passive transformation leaves invariant the dynamics of the phenomenon. This means that the *lawlike* connection (be it deterministic or indeterministic) between the initial and final state is invariant under a passive spatial translation transformation.

To most of the spatiotemporal symmetries, it is possible to give both an active and passive interpretation. This is not the case for time symmetry (nor, for example, for the spatial reflection symmetry). In fact, a passive interpretation of time-reversal does not make sense. Borrowing from Sklar (1976, p. 367), we are entitled to say that "...there is no standpoint of an observer such that the system and evolution, seen from this standpoint can be viewed as the 'time-reversed evolution' of the system." This is crucial to understand what the time-reversal of physical laws might tell us about the world: we should not expect to be able to 'see' time or some phenomena going backwards to believe that time symmetry can teach us something important about the world, as for instance, that there is no dynamical distinction between past and future.

The dynamical time symmetry has a well-defined active characterisation. Let's consider a system S, and let it evolve from its initial state $t(s_1)$ to a new state $t(s_2)$ in the time interval Dt. If we apply a time-reversal transformation, and the dynamics of the system is time-reversal invariant, then we can the take as the initial state $t(s'_2)$, which is the time-reversal of the final state of the original evolution of the system, and after the temporal interval Dt, the system will have evolved to $t(s'_1)$, the time-reversed version of the original state of the system. It is important to notice that, what is the relation between the original system and its time-reversed version depends on the theory under consideration. One of the difficulties in interpreting the physical significance of dynamical symmetries in general, and time symmetries in particular, is that to see whether the symmetries hold, important decisions have to be made. What counts as a time-reversed version of a system is an example of such a decision.

Now, given the conception of the block universe perspective we are assuming in this thesis, and Price's principle of no temporal double standards, the notion of time symmetry we are concerned with has to imply that, at the fundamental level, there is no distinction between past and future. As we said, the idea is that the fundamental dynamical laws do not pick out a preferred direction of time, so that positing a distinction between past and future would be similar to posit an absolute spacetime.

Special relativity. Special relativity is based on two foundational postulates, namely the principle of relativity and the light postulate. From them, it follows the Lorentz group of transformations, which are the transformations that leave invariant the dynamical laws of the theory. Minkowski proposed that this group of transformations encoded the geometrical structure of spacetime. Relative to an event E, there is a function that divides the events in spacetime into three categories: (i) events that are timelike separated, (ii) events that are spacelike separated, (iii) and events that have a lightlike separation. These three categories define Minkowski spacetime.

Events that are at a lightlike separation with E can be connected only by a flash of light, which establishes the limit of velocity in the theory. This means that a lightlike connection between two events constitutes the fastest relation between a cause and an effect allowed by the theory. Events that are at spacelike separation with E cannot be causally related since they lie in the absolute elsewhere of each other. The consequence is that if there is a spacelike curve, or, in other words, a dynamical relation between two events at spacelike separation, then the mediation between the events would have to travel faster than the velocity of light. For this reason, it is often said (specially in the quantum mechanics' literature) that such a relation implies action-at-a-distance. Finally, events that timelike separated with E are those that can be causally connected, since they can be related by any physical mediation that travels less than the speed of light. These events, plus the events at lightlike separation, can be either in the future or past light cones of E.

In a nutshell, the structure of Minkowski spacetime establishes that possible physical connections are at timelike and light like separation from each other, while it forbids physical relations between events at spacelike separation since they would require a connection travelling faster than the velocity of light. For a more extensive explanation of special relativity, we redirect the reader to (Torretti, 2000), (Maudlin, 2012), and (Ryckman, 2017).

General research question of the thesis. Can the block universe perspective provide a smooth reconciliation between quantum mechanics and special relativity? What would be the fundamental characteristics of a quantum theory that, by being compatible with the block universe, supply the conceptual elements for such reconciliation?

As it is widely known, although quantum mechanics and special relativity are not directly incompatible with each other, there is no agreement about how they can be reconciled. This led Shimony to claim that there is a *peaceful coexistence* between the two theories. Nevertheless, to what extent such a peaceful coexistence holds depends on the interpretation of quantum mechanics at stake.

The specific issue that our general research question addresses is whether the characteristics that a quantum theory would need to have in order to be compatible with the block universe perspective shed light on the puzzle of quantum non-locality. Roughly, quantum mechanics predicts that two systems that interacted in their past, and then separate from each other will remain 'connected' in the sense that any measurement of one of the systems seems to 'influence' the outcome of the other. Maudlin (2011, p. 22) identifies three weird features of this 'connection': (i) it is unattenuated by the distance, that is, the influence the systems exert on each other is not proportional to their distance; (ii) it is discriminating in the sense that the connection depends on the past – and, we shall ask, maybe the future? – history of the system; and (iii) it seems to entail faster than light spooks since the influence of one particle on the other appears to be *instantaneous*. The proof of the impossibility to provide a local explanation of this 'connection' is due to Bell. However, this proof bears an important assumption, namely, measurement independence, which consists in the independence of the properties of the system to depend on which property will be measured in its future. The characteristics of quantum mechanics in the block universe *might* directly challenge this assumption, enabling a local explanation for the 'quantum connection'.

The main motivation for looking at the block universe to see if we find clues about the relation between quantum mechanics and special relativity is that the latter theory is often interpreted as suggesting such a perspective about the metaphysics of spacetime. The reason is that special relativity teaches us that there is nothing as absolute simultaneity, and then, there is nothing that can be called an absolute present. Then, if we are interested in the reconciliation between these two theories, the block universe might turn out to supply a smooth element for it. Now, as we shall see, in some interpretations, the block universe requires fundamental time symmetry, so if quantum mechanics is a fundamental theory compatible with the block universe, it either must be time-symmetric or provide means to explain the asymmetry in terms of conventions or as associated with the thermodynamic arrow of time.

Anticipating some results, we shall find that whether the block universe perspective offers an interesting alternative to reconcile quantum mechanics and special relativity will depend on the answer we give to our specific research question. If the block universe requires time symmetry, and if quantum mechanics is time-symmetric, whether this explains the spacelike quantum spooks depends on what we take to be the consequences of time-symmetric quantum mechanics. Thus, if time-symmetric quantum mechanics exhibits retrocausality or action-at-a-temporal-distance, then the block universe does provide reconcile quantum mechanics and special relativity through a violation of the measurement independence condition. If such a theory shows temporal global correlations, the block universe does not play a reconciliatory role.

Specific research question of the thesis. Does time-symmetric quantum mechanics require retrocausality, spooky-action-at-a-temporal-distance, or mere temporal global correlations?

The general research question leads us to the more specific research question regarding the characteristics that a time-symmetric quantum theory might have. Depending on how we answer this question, the consequences for spacelike non-locality would be different. In the available literature, there are two alternatives, namely retrocausality and action-at-a-temporal-distance. Retrocausality is defined in terms of a violation of measurement independence, and action-at-a-temporal-distance, at least in some approaches, violates it as well. The former provides a local explanation for the violation of spacelike Bell inequalities. The latter, at least from a logical point of view, enables spacelike locality at the costs of introducing timelike non-locality, since it can be interpreted as violating measurement independence as well. Nevertheless, action-at-a-temporal-distance might not be considered as an explanation of spacelike non-locality, but just as its temporal counterpart. In this case, there would be both spacelike-action-at-a-distance and timelike-action-at-a-distance.

Let's consider first the retrocausality arguments. Price (2012) proposed that, under some assumptions, time-symmetric quantum mechanics *implies* retrocausality. Leifer and Pusey (2017), then propose a generalisation of the argument that takes the structure of a theorem, stating that a quantum theory cannot be time-symmetric without being retrocausal. Such a theory entails a temporal factorizability condition, analogue to spacelike factorizability, which is incompatible with quantum mechanics, in the same cases and for the same reasons that spacelike factorizability is.

Retrocausality is defined as the dependence of physical states on events lying on their future light cones. Operationally, the idea is captured in terms of the dependency of uncontrollable variables over controllable variables on their future. This characterisation shows that, in the context of quantum mechanics, if there is retrocausality, the measurement independence condition is violated.

Adlam (2018b) gives a different perspective to the retrocausality argument, arguing that they should be interpreted as evidence in favour of the non-Markovianity of the quantum domain. Whilst she embraces retrocausality, she argues that it does not have to be understood in temporally local terms. The consequence, she claims, is that time-symmetric quantum theories imply action-at-a-temporal distance.

We argue that time-symmetric quantum theories might not require retrocausality nor action-at-a-temporal-distance but temporal global correlations. These are correlations at the statistical level, which do not entail a violation of measurement independence. As such, they do not help in the project of reconciling quantum mechanics with special relativity. We provide a study case, which consists in the time symmetric collapse models proposed by Bedingham and Maroney (2017a).
In 2 we introduce the non-locality problem in quantum mechanics by means of the EPR argument and Bell's theorem. Additionally, following an argument proposed by Myrvold, we introduce the concept of spacelike global correlations, and show the differences with action-at-a-distance. In 3 we account for the retrocausal arguments, through an analysis of Price's setup (3.1) and Leifer and Pusey's theorem (3.2). After a criticism of one of the assumptions of Leifer and Pusey's theorem, namely their conception of time symmetry, we offer the modified retrocausality theorem (3.2.2). Then, we analyse Adlam's response to Leifer and Pusey's theorem, which consists in rejecting the λ-mediation assumption, such that we are not compelled to embrace retrocausality (3.3). Nevertheless, her argument implies that time-symmetric quantum mechanics involves action-at-a-temporal-distance. We propose that time-symmetric quantum mechanics, if it is temporally non-local, it does not imply necessarily action-at-a-temporal-distance. In 4, we introduce time symmetric collapse models, proposed by Bedingham and Maroney, and argue that they exhibit mere temporal global correlations.

2 Spatial non-locality

In this section, we introduce the EPR argument. Then, we discuss Bell's theorem in the deterministic and indeterministic context. Finally, we analyse an explanation of the spacelike violation of Bell inequalities proposed by Myrvold (2016).

2.1 Introduction to the quantum puzzle: EPR and action-at-a-distance

As is well known, quantum mechanics displays characteristics that made Einstein consider it as incomplete. The best known defence of this claim is the famous Einstein-Podolsky-Rosen (1935) (EPR) argument. However, Einstein already argued that quantum mechanics was non-local in the 1927 Solvay Conference. There, he claimed the thesis that quantum mechanics cannot be considered complete, without making any reference to entanglement. He rather proposed that, if the theory is accurate and complete, then the wave function needs to instantaneously collapse when it is detected by a measuring device. So, in a semi-sphere with many measuring devices on its internal surface, when there is a detection in one device, the wave function needs to instantaneously collapse, in a way that all the other detectors do not fire (see (Bacciagaluppi and Valentini, 2009)). In what follows, we shall focus on the EPR argument though, since it stays closer to our specific purposes.

What does it mean that quantum mechanics is incomplete? According to EPR, a complete theory is able to map every physical element of reality to an element of the theory. In this context, the EPR argument aims to show that the formalism of quantum mechanics forces us to accept either that the theory does not represent every relevant element of reality or that it is non-local. Locality is not only required by Einstein's already developed theory of special relativity, but it also seems to be an important element of the world and how we interact with it. Events can affect, cause or produce other events only if they are spatiotemporally contiguous to each other. In a letter addressed to Born, Einstein called this the 'principle of contiguity', and maintained that it is an essential condition for building scientific laws.[1] If we have good reasons to believe that two spatiotemporally separated events interact, then we posit a physical entity or quantity that connects them. In rough every-day life terms, we consider that there is a physical carrier that 'travels' from one event to the other, mediating an exchange of quantities.[2] Usually, these carriers, which could consist on some properties of an object evolving on time, are called ontic states, and are represented by the Greek letter 'λ'. This characteristic of locality, which is intrinsically related with our every-day notion of causality, is important for our study and it is going to be called λ-mediation.

This section gives a brief introduction to the structure of the EPR argument by following a contemporary reading (mainly (Redhead, 2020)). We do not aim to delve into all the conceptual details, nor to be historically accurate. As the reader may know, the subtleties of the paper, the historical details, Einstein's opinions about it, its reception and motivations, could be the subject of an entire thesis (and even more). After this concise exposition, we shall explore what alternatives were left open and how Bell reacted to them.

The crucial idea of EPR is that quantum mechanics is not complete and this feature makes the theory appear non-local. Let's unpack a little bit some concepts. Non-locality means in this context that the theory exhibits correlations that seem to be incompatible with the structure of Minkowski's spacetime. For instance, if we take two events at spacelike separation, and we find that by performing some operations on one of them something changes on the other, then there ought to be a mediation between them. The special theory of relativity tells us that such a mediation cannot travel faster than the speed of light. So, if there are instantaneous changes caused

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[1] See (Maudlin, 2011, p. 7), and references therein.

[2] For an introduction to causation in physics see (Frisch, 2020).

by events at spacelike separation, these ‘spooks’ are incompatible with the special relativity (see 1).

A second ingredient of EPR is the notion of incompleteness, which means that there are elements of reality not represented or captured by the concepts and models of the theory. The elements of reality are identified by our ability to predict with certainty the outcome of a possible measurement without disturbing them. That is, a quantity a exists if we can predict with certainty the outcome $A = a$. The reason for this is that if we can predict something with certainty, then there must be a physical fact that explains this certainty.

With this background, we can already see that what the EPR reasoning needed was to point out elements of reality which do not have a counterpart in the theory. And then, it would be possible to claim that those facts of the matter that are missing explain why the theory seems to be non-local. To do so, they consider a thought experiment consisting of separated particles with correlated position and momentum. In line with (Redhead, 2020), we will rather consider Bohm’s reconstruction in terms of a pair of spin-1/2 particles prepared in the singlet-state travelling in opposite directions in space. This construction will enable us to move in a smooth way to the argument by Bell (1964).

Following the quantum formalism, if we perform a measurement of one component of the spin of a particle, let’s say the z-component, then we can predict with certainty the outcome of a measurement of the same component on the correlated particle. In other words, once one measurement is performed we can with certainty predict the outcome of a measurement on the other particle. From this we infer that the outcome of a potential second measurement corresponds to an element of reality. And this possibility does not change, disregarding how distant in space the two particles are. Therefore, if our theory is local, then the element of reality that can be predicted with certainty must have existed before the performance of the measurement. However, and this is the important point, those elements of reality that *must* exist previously to the measurement do not have a counterpart in the theory, that is, there is nothing in the wave function (nor in another theoretical element) that represents them. Inversely, if the theory provides a complete picture of what is going on, we must infer that the act of measuring one particle, which is associated with our ability to make a certain prediction, instantaneously creates an element of reality ascribed to the distant entity. Hence EPR’s conclusion: granting locality, quantum mechanics is not complete.
Schematically, we can reproduce the argument as follows:

> (I) A complete theory represents every element of reality of the relevant physical phenomena, elements of reality being those quantities that can be predicted with certainty.
>
> (II) According to the formalism, particles prepared in the singlet-state and

> measured in different spatial locations are correlated in a way in which, once a measurement is performed on one spin-component of one of the particles, we can predict with certainty the outcome that a measurement, if performed, of the same spin-component of the other particle will give us.
>
> (III) Given locality, it cannot be the act of measurement on one particle which creates the element of reality of the other particle. If that were the case, the theory would involve a 'spooky-action-at-a-distance' that seems incompatible with special relativity. Therefore, the element of reality must exist from the moment in which the particles were prepared and locally interacted.
>
> (IV) Nevertheless, the quantum formalism does not have a counterpart of this element of reality until the measurement of the component of one of the particles is performed. Hence, quantum mechanics is not complete.

The structure of the aforementioned argument takes locality for granted. Elements of reality and their interaction are supposed to take place in the spacetime arena, and, naturally, EPR did not find attractive the option of denying its structure. special relativity tells us that the structure of spacetime should constrain every physical description of events. From that feature, plus the formalism of quantum mechanics, the incompleteness of the theory follows. However, if instead of assuming locality, we take for granted that quantum mechanics is complete, then the conclusion leads to the non-locality of quantum mechanics.
As Redhead (2020, p. 469) schematises:

> (A) Quantum formalism + locality $\rightarrow \neg$completeness.
>
> (B) Quantum formalism + completeness $\rightarrow \neg$locality.

To be clear, the reason for (B) is that we can interpret the theory as giving us complete information about every element of reality, and then we can only predict with certainty the value of a particle once the other has been measured. Given that the particles are at the absolute elsewhere of each other, the act of measuring one of them would have to bring to existence the element of reality that can be predicted post-measurement. This creation of the element of reality by a measurement in a spatially separated region would be a non-local feature of quantum mechanics. But, is there any single way to understand 'non-locality'? If the world is non-local, what kind of physical relations are allowed? Is there a single definition of what locality is and what correlations it restricts? If there is more than one definition, which one of them does (B) ask us to give up and what physical restrictions does it impose? There is no consensus about how to answer these questions. In section 2.3, we shall present one answer provided by Myrvold (2016).

As we said, Einstein held option (A) even before 1935, so he regarded that quantum mechanics needed to be completed and this completion was expected to explain the correlations in deterministic and local terms. Option (B) was endorsed by Bohr and the so-called Copenhagen interpretation.[3] This approach denied the EPR criterion of reality and the implication of the incompleteness of quantum mechanics.[4] In fact, it is possible to consider the correlations as brute facts that do not need to be explained. Given that the EPR argument – and Bell's original theorem – is based on *perfect* correlations, this answer seems unsatisfactory from a realist stance (*à la* Einstein and Bell), which would regard them as a miracle if they are not susceptible of an ontic explanation. These two alternatives do not change the formalism of quantum mechanics. We are calling orthodox quantum mechanics (OQM) the view that quantum mechanics is complete, and does not require a deeper explanation. Another alternative is due to de Broglie-Bohm pilot-wave theory (dBB), which adds additional variables to the theory in order to keep determinism and the EPR criterion of reality. However, as we are going to see in the next section, such a completion of OQM did not realise EPR's hopes of locality. In such a theory, the measurement of one particle disturbs the correlated particle regardless of how far apart are from each other. In a general sense, dBB is in line with (B) because it provides a completion of quantum mechanics by the introduction of the particle's position, without being able to restore locality.[5]

So far, we have introduced the locality problem in quantum mechanics in relation with the EPR argument. The motivation to start with EPR is not only historical, but, as it is going to become clear in due course, the argument makes a crucial assumption. Einstein supposed that future events cannot influence past events in the same way as past events affect future ones. The standard way of framing this is that there is no-retrocausality in reality. In a rhetorical way, Price and Wharton (2017) claim that this was a clue that Einstein missed, having him all the theoretical elements needed at the time. Following such a clue would have enabled him to jointly maintain his criterion of reality, and that quantum mechanics was local. But let us leave aside this for the moment.

In the next section we jump forward in time to Bell's theorem, which shows that, granting the relevant assumptions (among them, no-retrocausality), Einstein's desire is not possible. As we mentioned, that is the case with dBB. If quantum mechanics is supplemented in a way that it respects the EPR criterion of reality, it must involve

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[3] We assume that there is something called the Copenhagen interpretation, although whether such a unitary view of quantum mechanics exists has been put into doubt by Howard (2004).

[4] See, for example, Bell (1981, p. 155), where he also confesses that he has never understood Bohr's view.

[5] This brief summary is based on my notes of Bacciagaluppi's course "The Quantum World" at Utrecht University.

non-local correlations. In fact, the first developments of Bell's theorem were originally devoted to evaluate whether any completion of quantum mechanics in terms of deterministic additional variables displayed the same non-locality as dBB theory. Later, from this original motivation, Bell generalises the theorem to stochastic models, rendering it independent of whether a theory exhibits perfect EPR (anti)correlations, or not (see (Brown and Timpson, 2016)). In this case, given certain assumptions (which are going to be of utmost importance for our study), Bell concludes that any realist stochastic theory involves statistical dependencies between the measurement of particles at spacelike separation. It is clear that these statistical dependencies amount to non-locality: the controversial issue is whether these non-local correlations (which cannot be screened off by common causes, as we are going to explain) are instances of 'spooky-action-at-a-distance', or not. At this point, the discussion about the different meanings of locality start to be crucial to understand the (in)compatibility of quantum mechanics with special relativity.

2.2 Bell's theorem

In this section we present Bell's theorem for deterministic and indeterministic models. Our exposition follows mainly (Bell, 1964), (Bell, 1976), (Bell, 1990), (Butterfield, 1992), and (Brown and Timpson, 2016), although we also take into careful consideration (Myrvold, 2016),(Myrvold et al., 2021), and (Redhead, 2020).

In the EPR-type arguments, a consequence of completeness (and the criterion or reality) is that the non-locality takes the form of action-at-a-distance, in the sense that the measurement of one particle brings to reality a physical element on a distant particle. On one hand, if the theory is complete, then it is non-local; while on the other, if the theory is non-local, then it is not complete. As we saw, Einstein assumed locality as a premise. Unlike Bell's theorem, this type of proof does not require the derivation of an inequality so it seems conceptually simpler.[6] Nevertheless, it is also weaker, in the sense that Bell's theorem shows that a complete (be it deterministic or indeterministic) and non-local theory is not compatible with the predictions of the quantum algorithm. This was not possible to be proven by the EPR-type arguments alone, which required perfect (anti)correlations. The consequences of Bell's theorem are imponderable. They revitalise and attribute importance to the foundations and philosophical enterprise of understanding quantum mechanics and its relation with special relativity.

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[6] Note that EPR-type arguments are not the only way of proving non-locality without inequalities. The non-local character of OQM can be proven even without making reference to entanglement, (for example by the already mentioned Einstein's single-slit experiment exposed in the 1927 Solvay Conference, Gleason's theorem, Einstein boxes, and de Broglie boxes thought experiments).

Our aim in this section is to explain Bell's theorem, bearing in mind the distinction between deterministic and indeterministic models, as well as their connection with the different conceptions of 'locality' used in 1964-1971 and the 'local causality' condition from 1971 on. This brief exposition is going to be essential for the discussion about the assumptions of Bell's theorem, specially measurement independence. Regarding the general question of this thesis, the relevance of this assumption lies in Price's set up and Leifer and Pusey's theorem, which claim that, under certain assumptions, time-symmetric quantum mechanics require retrocausality. This would mean that in a quantum theory compatible with the block universe the physical states are causally dependent on the settings of measurements performed in their future light cone. Concerning the specific research question, we shall argue that time-symmetric quantum theories, do not necessarily need to involve retrocausality, but mere temporal global correlations, which amount to temporal non-locality, but not action-at-a-temporal-distance.

2.2.1 Non-locality in Bell's deterministic models

Between 1964 and 1976, Bell analysed deterministic quantum models. He was evaluating whether every completion of quantum mechanics, which restores determinism, entailed non-locality. Bell's theorem was motivated by the realist programme in which EPR was circumscribed. Almost two decades after EPR's paper, Bohm (1952) developed a deterministic theory that posited additional variables (also called hidden variables), which was based on previous work by de Broglie. Those additional variables, which consist in the position of the particles, enabled the application of EPR criterion of reality (see Goldstein (2021) and references therein). Although in this context determinism was safe, there was uncertainty about whether any theory that introduces additional variables was incompatible with locality, as Bell (1966, p. 11) expressed.

Generally speaking, Bell (1964) showed that the EPR's hope was not possible to achieve: every theory that introduces additional variables to restore the theory of causality (associated with determinism) *and* locality is "shown to be incompatible with the statistical predictions of quantum mechanics" (Bell, 1964, p. 14). If we consider a pair of particles prepared in the singlet state (spin-1/2) travelling in opposite directions towards the L- and R-wing of an experiment, and then being measured, the outcomes are going to be strictly (anti)correlated. Once we measure the z-component of the spin of one particle in the L-wing, we can predict with certainty the outcome of a measurement performed on the same component on the R-wing. Now, to introduce locality we need to consider that the outcomes were predetermined by the additional variables of the particles, and thus they were not brought into reality by the performance of the measurement in the distant wing. The determination should have taken place when the particles interacted with each other at the preparation, although these elements would have to be hidden in the theory, since they were not shown in the wave function. Bell's famous result is that such a theory is incompatible with the predictions of the quantum algorithm. Therefore, any theory that completes OQM with additional variables has to violate locality. The inequalities formulated by Clauser et al. (1969), and the implementation of an experimental setting by Aspect et al. (1982), permitted to test empirically whether the predicted inequalities were met or not. Since then, the predictions of the quantum algorithm have been corroborated in several ways. Consequently, *accepting the assumption of the theorem* the consensus is that local additional variables theories have been experimentally falsified.

The original strategy of the theorem goes as follow: Bell first takes the quantum formalism, and applies the following assumption, which is meant to guarantee locality: the freely chosen settings of the measuring device at one wing of the experiment cannot influence the outcome of a measurement of a particle at the distant wing. In order to meet this condition, he introduces the additional variables, which, in conjunction with the chosen component to be measured (i.e., the settings of the measuring device), should completely determine locally the outcome of the measurement. What this guarantees, crucially, is that the elements of reality on, say, the R-wing do not depend on which component was chosen to be measured at the L-wing. After this, Bell shows that the predictions of such a model are incompatible with the predictions of quantum mechanics. This is proved by the derivation of an inequality from the predictions of the described model, and a consequent violation of this inequality by quantum mechanics. The standard interpretation is that as a result of this incompatibility, there are two options: either we reject the quantum algorithm or we give up the locality condition. Thus, the empirical violation of the inequalities counts as an empirical disconfirmation of the possibility of a local additional variables theory.

Some points are worth to be made now. First, as Duhem's work showed back to the beginning of the 20th century, scientific hypothesis cannot be tested in isolation.[7] In the context of Bell's theorem, the moral is that the assumption of locality cannot be ruled out without auxiliary assumptions. After Bell's first formulation, it has been widely recognised that the theorem had some hidden assumptions. The most known is the independence of the additional variables on the settings of the measuring device; a condition that is called measurement independence. A theory can violate this condition by different mechanisms. Specially significant for the purposes of this thesis is its violation through retrocausal effects. In interpretations that introduce retrocausality, the violations of Bell inequalities are explained by the putative fact that that the settings of the measuring devices have effects backwards in time over the additional variables of the theory. Within this framework, such a theory provides

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[7] See (Duhem, 2016)

a better explanation for Bell's results since it does not introduce non-locality.

Secondly, as we already mentioned in the previous section, even if we agree that the results evidence that the quantum world is non-local, what 'non-local' means is not an uncontroversial issue. The question regarding what locality means, and therefore what is the foundational significance of the theorem has been subject of increasing attention over the years. Even Bell's own comprehension of the matter changed along his work (see (Brown and Timpson, 2016)). The issue is not trivial, but there is one point that seems to be clear: in 1964, when Bell considered deterministic models, non-locality implied action-at-a-distance (as in the EPR argument). Thus, assuming measurement independence, the conclusion considering these models in the words of Bell (1964, p. 20) is the following:

> In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously, so that such a theory could not be Lorentz invariant.

What Bell points out is that when an experimenter chooses the component that they want to measure, and sets the measuring device accordingly, the act of measuring the particle at the corresponding wing does not affect the physical properties of the particle at the distant wing. In brief, the *outcome* of a measurement at, say, the L-wing does not depend on the *parameters* of the measurement that was previously performed at the R-wing. As we shall see in 2.3, this is an asymmetric relation between parameters and outcomes that is usually associated with causality. The structure of spacetime according to special relativity is understood as ruling out the possibility such causal connections.

It is not necessary to introduce a more detailed account of the deterministic models since they constitute a special case of the indeterministic ones. In the next subsection, we shall delve into indeterministic models, and their locality condition, namely, factorizability. This is relevant for our study since it will provide the background of the discussion. We will argue that, if we accept that the block universe perspective requires time symmetry, and if time-symmetric quantum mechanics requires any sort of retrocausality (be it λ-mediated or not), then this temporal perspective gives a smooth explanation of the violations of spacelike Bell inequalities by quantum mechanics.

2.2.2 Causal locality and factorizability in Bell's generalised models

The generalisation to indeterministic models took place in steps. For example, in (Bell, 1971), the stochastic elements were reducible, since they were introduced by averaging over the additional variables ascribed to the apparatus. As (Brown and Timpson, 2016, p. 97) point out, first articulation of the elements for the construction of indeterministic models were due to (Clauser and Horne, 1974). In their work, they also identify for the first time the two conditions for factorizability, namely, parameter and outcome independence, which were hidden in Bell (1971).

(Butterfield, 1992) remarks that the relevant difference between deterministic and indeterministic models is that the latter introduce two stochastic elements, whereas the former only one. In his own words, "the deterministic/stochastic distinction is really a matter of whether or not λ fixes the measurement-results" (Butterfield, 1992, p. 54). Deterministic models introduce a probability distribution for the additional variables at the initial state, and then they evolve over time following a deterministic law. Once a measurement is performed, the hidden variables completely determine the outcome. Indeterministic models, on the other hand, ascribe stochastic elements to both the distribution of possible states and the determination of single and joint results.

Another important ingredient in the stochastic models is that the inequalities follow through factorizability, whilst the deterministic models derive them only from the locality assumption (plus, as we mentioned, measurement independence).[8] As we saw in the previous subsection, in the deterministic models locality was understood as a relation between the parameters at one wing with the measurement outcomes at the other. Correlations between outcomes were not directly considered, since their relevance shows up only in indeterministic models. In order to include correlations between measurement outcomes – independently of correlations between settings and outcomes – factorizability was needed.

There are two important elements to have in mind. First, factorizability is a condition derived from local causality, which is an analogue of the locality condition of deterministic models that we already discussed. Second, the definition of local causality uses Reichenbach (1956) principle of common cause (PCC). So, in order to answer the question 'what is factorizability?' we shall introduce first local causality and its relation with the PCC.

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[8] The proper formulation of the factorizability condition was still hidden in (Bell, 1971), were the quantum theory under consideration was not irreducibly stochastic yet (since, as we said, the indeterministic elements were introduced by averaging over the uncontrollable variables of the measuring apparatus): "...Bell took as his locality condition that these averages predictions on one system did not depend on the controllable settings of the distant measurement device. But another assumption was hidden in the derivation: that such averages of pairs of simultaneous measurements on the distant systems factorize" (Brown and Timpson, 2016, p. 97).

The PCC claims that if two variables are correlated and neither is cause of the other, then they must share a common cause. When the common cause is considered into the analysis, the statistical correlation between the mentioned variables disappears. We say then that the common cause screens-off one variable from the other. It is a subject of discussion whether the PCC exactly as it was considered by Reichenbach (1956) applies or not to Bell's correlations or EPR, although the principle is *de facto* usually applied without major problems (see (Brown and Timpson, 2016, p. 106) and (Butterfield, 2007)). Just like its label indicates, the principle assumes that the correlations should be causally explained – at this stage it is not necessary to specify a precise notion of causality. Bell defines local causality, from which factorizability is derived, by means of the PCC, as it is explicitly shown in (Bell, 1976, pp. 55-6): if we take two events, A and B that are localized at two spacetime regions, 1 and 2, with a spacelike separation, then A and B cannot be causally connected. This is due to the structure of Minkowski spacetime. If it happens to be the case that there are statistical correlations between these two events, as it occurs in quantum mechanics, then they ought to be screened-off by a common cause in the common backward light cone of the events. That is to say: under a complete the specification of the beables in the overlap of the light cones of A and B, the correlation between these two events should disappear. In a locally causal theory every correlation between events that lie outside their light cone regions should be explained by the presence of a common cause that is in their common past.

Factorizability is an element representing the local causality condition in the derivation of the inequalities. As it is often recognised, factorizability does not constitute a definition of local causality, but it is a consequence of it (see (Myrvold et al., 2021)). On one hand, factorizability by itself does not make any reference to causes and effects, which are the terms in which local causal is explicitly formulated. On the other, it is indeed a consequence of locality in the sense that if two events do not interact, then there ought to be no statistical correlation between them provided that we give a complete specification of the relevant elements, that is, the common causes. As we just said, the physical impossibility for them to directly interact is given by the spacetime structure of special relativity. The only possible local interactions are those that respect the light-cone structure. It may be important to note that, as it is defended by Brown and Timpson (2016), and Myrvold et al. (2021), *contra* Maudlin (2011), and Norsen (2011), the notion of locality in these models is not the same as the one employed in the deterministic cases. As Bell (1976, p. 54) explicitly states, local causality is a generalization of *local determinism*, and locality is a special case of local causality.

Factorizability entails that the probabilities for all λ, a, b, and all results A and

B meet the following condition:

$$pr_{\lambda ab}(A,B) = pr_{\lambda a}(A)pr_{\lambda b}(B), \tag{1}$$

which is also expressed in the literature, for instance in (Bell, 1990), as:

$$pr(A,B|a,b,\lambda) = pr(A|a,\lambda)pr(B|b,\lambda), \tag{2}$$

where, again, $pr(A,B)$ is the joint probability for outcome A, conditional on the settings of the measuring device, a, and outcome B, given b. A and B are independent if we take into consideration the free variables, a and b, and, crucially, λ. Both expressions differ on whether we should assign a probability distribution over a, b, and λ (see (Seevinck and Uffink, 2011, p. 8)).

To make predictions, we average over λ and we get:

$$pr_{ab}(A,B) = \sum{}_{\lambda} pr_{ab}(A,B)pr(\lambda) = \sum{}_{\lambda} pr_{\lambda a}(A)pr_{\lambda b}(B)pr(\lambda). \tag{3}$$

This way of writing factorizability is going to become important when we consider timelike Bell correlations and the timelike factorizability condition in 3.2.

Analogously to the deterministic scenario, quantum mechanics violates the inequalities derived from factorizability, compelling us to reject one of the assumptions. Similarly to the previous models, measurement independence is also assumed[9], so that any theory in which the probabilities for a joint measurement at spacelike separation factorize, *and* respects measurement independence, cannot reproduce the predictions quantum mechanics. The usual interpretation of these models is giving up factorizability, and thus, local causality.

Nevertheless, these models offer an interesting subtlety: factorizability can be derived from the conjunction of two conditions labelled parameter independence and outcome independence.[10] Such a distinction turned out to be very fruitful for the research regarding what the violations of Bell inequalities amount to. In this context, the violations of Bell inequalities can be due to the violation either of parameter independence or outcome independence. The physical significance of these two cases varies. Let us see how these conditions are defined.

Parameter independence: In order to make explicit that the marginal probabilities for any λ, a, b and b' are the same for any result A, we shall formulate it as

$$pr_{\lambda ab}(A) = pr_{\lambda ab'}(A), \tag{4}$$

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[9] In the sense that $pr(\lambda)$ is assumed to not depend on a or b.

[10] These two conditions were introduced by Jarrett (1984) under the labels of locality and completeness, correspondingly, although they can be tracked back to Clauser and Horne (1974). Then, Shimony (1984) strengthened them recognising the controllability and uncontrollability they involve, and he relabelled them with the terminology we are employing in this thesis.

and similarly for b and any a, a' for any result B. This formulation makes explicit that if we have a complete specification of λ, and we keep it fixed, together with a and b, the marginal probabilities for A (and B) are independent of b (and a, correspondingly). In other words, the marginal probabilities do not depend on the parameters of the measuring apparatus that is spatially separated.

Bell (1990) puts it as follows:

$$pr(A|a, b, \lambda) = pr(A|a, \lambda), \tag{5}$$

$$pr(B|a, b, \lambda) = pr(B|b, \lambda). \tag{6}$$

This means that given λ, a and b, the result A in the L-wing is statistically independent of whether a measurement is performed on the R-wing, or not, and if performed, it is independent of the result. The same reasoning goes for B. Given the specification of λ and a, the correlation between A and b disappears. Using the introduced terminology, this means that λ is a common cause of A and b, so conditioning on it screens-off the measurement-setting correlation between the two wings.

Outcome Independence: Given λ, a, and b, the information about any measurement outcome B is irrelevant for the probability that the model attributes to measurement outcome A,

$$pr_{\lambda ab}(A, B) = pr_{\lambda ab}(A) pr_{\lambda ab}(B) \tag{7}$$

So, if the single probabilities are not 0 or 1, then:

$$pr_{\lambda ab}(A| + 1) = pr_{\lambda ab}(A| - 1), and \tag{8}$$

$$pr_{\lambda ab}(B| + 1) = pr_{\lambda ab}(B| - 1). \tag{9}$$

The reason why this condition was formerly called completeness is that it maintains that if the model is complete, meaning that it provides a complete specification of the relevant λ, a and b, then any new information about the outcome at one wing is *redundant* for the probabilities at the other wing.[11]

Like we did with parameter independence, let us restate this condition with the formulation of Bell (1990):

$$pr(A|B, a, b, \lambda) = pr(A|a, b, \lambda), \tag{10}$$

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[11] To what extend λ is expected to be complete or sufficient – for certain purposes – is a matter of debate, which is intentionally omitted here. We redirect the reader to (Seevinck and Uffink, 2011) for further analysis.

$$pr(B|A, a, b, \lambda) = pr(B|a, b, \lambda). \tag{11}$$

This expression makes explicit that conditioning over a complete λ, screens-off the correlation between the outcomes at the two wings. Then, when the measurement outcomes at the wings are correlated, this is not due to direct causation between them, but due to a common cause.

With these definitions in mind, the moral of Bell's theorem can be interpreted as compelling us to give up either parameter independence or outcome independence. Depending on which one of them is violated, the characterization of the non-local character of quantum mechanics changes. We can appreciate that a violation of parameter independence is analogue to the violation of the locality condition in the deterministic models. As we have seen, this condition is understood as the independence of the measurement outcome at one spacetime region over the settings of the measurement device at the other region. Thus, as in the case of parameter independence, what is at stake is a relation between settings and outcomes at spacelike separation. It is in this sense in which deterministic locality is an instance of local causality, and the deterministic models a case of the stochastic models.

Crucially, the violation of parameter independence, like the violation of locality in the deterministic case, is often taken to imply action-at-a-distance. The specific reasons for this may change in the literature, although the common basis is that violations of parameter independence can be used for signalling between two regions lying at the absolute elsewhere of each other. This feature led Shimony (1984) to characterise the transgression of this condition in terms of controllable non-locality. An experimenter at one wing is able to signal to the other experimenter at the other wing by means of the manipulation of the knob settings of the measuring device, since this manipulation would change the probabilities for the measurement outcomes. The signals in question would have to be superluminal or instantaneous since the two wings are at spacelike separation. So, the rough conclusion: violations of parameter independence imply action-at-a-distance.

In conclusion, Bell's theorem tells us that from parameter independence, outcome independence, and measurement independence follows an inequality that is incompatible with the predictions of quantum mechanics. Within these indeterministic models, the range of interpretations that are possible is enlarged, since the violation of local causality can be understood as a violation of parameter independence or outcome independence. The consequences for the non-local character of quantum mechanics are, thus, different. In the next subsection, we shall review one of the traditional arguments about which condition is violated and what this means regarding the compatibility between quantum mechanics and special relativity. After this quick survey we shall focus on recent arguments defending that Bell's theorem teach us that the quantum world is retrocausal, that is, that it violates the measurement independence assumption. Along with the violation of measurement independence it is usually maintained that quantum mechanics respects, after all, local causality, although it displays weird features, such as dependencies of present states on future events or superdeterminism.

2.3 Non-locality, action-at-a-(spatial)-distance, and global correlations

The perplexities generated by quantum mechanics have not diminished over the years. The conceptual progress in the understanding of what the puzzles are, and what would constitute a solution to them has not produced agreements throughout the philosophical community. In the previous sections we presented the mystery of quantum non-locality, and in 4.1 we shall introduce the quantum measurement problem. The present subsection aims to show that, associated with the distinction between parameter independence and outcome independence, it is possible to understand the non-locality implied by Bell's theorem in terms of action-at-a-distance or global correlations. Global correlations are a candidate for explaining the violation of Bell inequalities in a way that is non-local but does not require action-at-a-distance. Thus, the conceptualization of non-locality and its relation with special relativity changes according to these two different views. Our analysis is exceptionally narrow and it does not do justice to the subtleties of the debate, although it shall add an important idea to our study: the non-locality of quantum mechanics does not need to entail action-at-a-distance, it can be understood in terms of mere global correlations as well.

Myrvold (2016) argues that quantum mechanics is non-local, but it does not imply action-at-a-distance. His argument is part of his programmatic defense of dynamical collapse theories, which are based on a modification of the Schrödinger equation through the introduction of non-linear and stochastic elements. For a detailed exposition of these theories see 4.2. The argument is based on the idea that causality is a temporally asymmetric notion, which is incompatible as a relation between spacelike separated events since it implies a fixed temporal order. "On the usual notion of causation, a cause must temporally precede its effects, and so, if an event p is a cause of an event q, we must have $p \prec q$" (Myrvold, 2021, p. 101). The relation of precedence is taken to be given by Minkowski spacetime, and it is, according to Myrvold (2021, p. 101), asymmetric: "if $p \prec q$ then it is not the case that $q \prec p$". The general point is that violations of parameter independence imply causality, and consequently *a causal arrow.* It is this causal asymmetry which is incompatible with Minkowski spacetime structure. Furthermore, this causal relation would imply action-at-a-distance, since it would have to be a superluminal causal relation. However, the argument goes, quantum mechanics does not violate parameter independence, but outcome independence, which *cannot* be conceptualized in causal terms precisely because the relation between outcomes does not imply a fixed causal arrow. Given that in Bell's theorem the two wings of the experiment are at spacelike separation, there cannot be a fixed causal priority from one of them over the other; none of them could be identified as *the* cause, and *the* effect in the relation since special relativity forbids such a categorization between events at spacelike separation. Therefore, violations of outcome independence do not imply causal priority, since measurements at spacelike separation commute; it does not matter which of them is measured first. Thus, although quantum mechanics implies non-local correlations, since the measurement outcomes of the two wings are correlated, it does not imply action-at-a-distance.

In more detail:

(I) A violation of Parameter Independence requires a fixed causal direction, that is, an arrow of causation. This becomes evident once we consider that in a Bell experiment such a violation can be used for signalling from one wing to the other. "Signals are special cases of cause-effect relations; the sender chooses between various settings of the signalling device, and the signal obtained by the receiver is informative about the sender's choice" (Myrvold, 2016, p. 240). So, the event identified as the cause is the act of setting the apparatus by an experimenter in one wing, and the effect is the changes on the probabilities of possible outcomes upon measurement on the other wing. Thus, there is an event which is a cause, and there is another that is an effect, *and this cannot depend on the frame of reference.* Setting the measuring device, say, the event p, affects the measurement outcome, q. Therefore, $p \prec q$: there is a fact of the matter about which happened first, being the cause, and which happened after, being the effect. (Notice that for Myrvold this causal arrow is intrinsically attached to an arrow of time, as we shall comment shortly). But the impossibility to flip the cause with the effect is incompatible with the spacetime structure of special relativity; both events are at spacelike separation, and which one takes place first depends on the chosen frame of reference. According to special relativity, the relation $p \prec q$ can only hold between events at timelike or lightlike separation, and it is forbidden between events at spacelike separation. Simply put, there cannot be a *fixed* causal arrow between the two events. Moreover, given that violations of this condition imply causality, this causal relation must be superluminal, and imply action-at-a-distance: "It is this [the asymmetry of causation] that motivates the claim that special relativity forbids action-at-a-distance; without it, there is no reason to think that causal relations between spacelike separated events are incompatible with relativistic spacetime structure" (Myrvold, 2021, p. 101).

(II) A violation of Outcome Independence, on the contrary, cannot count as a causal correlation since it is not possible to identify one measurement outcome as being the cause of the correlation with the other measurement outcome. Given that this condition is not compatible with causality, it does not imply action-at-a-distance. quantum mechanics establishes that if two measurements are performed on a bipartite system at spacelike separation, which measurement takes place first does not change the joint probabilities distribution. This is due to the commutation of the operators at spacelike separation, which entails that there is no asymmetric relation between the order in which the measurements are performed at two different wings. As a consequence, there is no fact of the matter about which is the cause and which is the effect. We are facing non-local correlations without action-at-a-distance. These correlations are characterised as global and they do not implicate an incompatibility with special relativity since they do not exhibit a fixed temporal order (there is no temporal priority of one event, the cause, over the other, the effect). In (Myrvold, 2021, p. 109) words: "Unlike cause-and-effect relations as usually conceived, the relation of probabilistic correlation between these distant events is symmetric, and does not require temporal order between the events. For this reason, it is misleading to assimilate this relation to the causal relation and refer it as nonlocal 'influence' or action-at-a-distance."

The theory that accounts for OQM according to Myrvold is irreducibly stochastic and it does not violate parameter independence, but outcome independence. In this sense, it is compatible with special relativity.[12] This result is perfectly in line with Shimony's views. Redhead (2020, p. 475) comments that the reason why Shimony seems to have called the correlation 'harmony-at-a-distance' or 'passion-at-a-distance' is exactly its non-causal and symmetric character. However, we concur with Redhead who states that we can still wonder whether this is a completely satisfactory answer: "Shimony's nomenclature phrase 'passion-at-a-distance' seems exactly the right one to capture what is going on, even if one concedes that the mystery of the EPR [and Bell's] correlations is not eliminated merely by introducing an apt nomenclature." (Redhead, 2020, p. 475). Of course, qualifying the non-local character of quantum mechanics as being a product of *global correlations* does not change too much the state of affairs. This is the reason why we are still on the enterprise of finding an alternative explanation.

Before continuing we shall bring the reader's attention to a subtle point. Myrvold bases his argument on the strong condition that causality is a time-asymmetric relation between two (or more) events. This means that if A is a causal factor to bring up B, then B cannot be a causal factor of A, and A has to take place prior to B. Causality is taken here as being *intrinsically attached to time*; a cause needs to precede the effect with respect to a 'master' time's arrow. This is a stronger condition than claiming that causality is an asymmetric relation between two (or more) events. Whilst the former condition says that a cause always precedes the effect *in time*, the

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[12] For a detailed defence, that goes beyond the analysis of the non-local correlations of a Bell's setup, of how the collapse postulate is compatible with relativity , see (Myrvold, 2002).

latter only holds that cause and effect are not interchangeable, for instance, under a time-reversal transformation. The weaker condition establishes that causation implies an arrow from cause to effect that is asymmetric, but it does not need to be attached to a fundamental arrow of time.[13] Whereas the stronger condition rules out by definition retrocausality – and this is one of the motivations of Myrvold (2016), see (p. 240) – the weaker does not. According to Myrvold, this is crucial in the analysis of what the violations of Bell's theorem tell us: "[causality] is temporally asymmetric; the cause must precede the effect. On such a notion, the temporal precedence constrains the relation of potential causal influence; an event x is a potential causal influence on y only if it is in the past of y. *It is this feature of causation that precludes causal influences between spacelike separated events in a relativistic spacetime.*" (Myrvold, 2016). Bearing this in mind, if we do not accept that the asymmetry of causation must be attached to a preferred time orientation given by a master arrow of time, then relativity might not rule out causal relations between spacelike separated events. This means that Myrvold's argument might hold only with the strong condition, and we believe this is a relevant conceptual limit of the proposal, which might be taken as a motivation for the search of other alternatives.

Along this chapter, we introduced one of the fundamental puzzles of quantum mechanics, namely, its non-local character. In the first section, we presented the EPR analysis and the aim of having a complete and local quantum theory. We discussed Bell's theorem and how he showed that EPR's hope was not achievable both with deterministic or stochastic completions of quantum mechanics. We ended this chapter with a brief and broad discussion about the differences between the violations of parameter independence and outcome independence, and what are the consequences for the notion of non-locality and their relation with special relativity. In the next section, we will see how time-symmetric quantum theories can face this puzzle. Remember that our general aim is characterising quantum mechanics in the block universe, and analyse what options it give us to face the incompatibility between quantum mechanics and special relativity. The next chapter is devoted to account for the first characteristic that such a theory should meet, namely, fundamental time symmetry, and explore what are the consequences of time-symmetric quantum mechanics.

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[13] We redirect the reader to (Farr, 2020), where it is argued that causation implies a time-orientation and it is not compatible with causal-time-reversal. A time-reversal of a causal relation should be understood as a different state of affairs from the original one. In this sense, causality is better understood within the B-theory rather than the C-theory of time. See also (Frisch, 2014), and (Frisch, 2020).

3 The (in)dispensability of retrocausality for time-symmetric quantum models

More than a decade before Bell's first version of his proof that a completion of OQM cannot avoid some sort of non-locality, de Beauregard (1953) proposed the idea that the EPR perfect (anti)correlations are not necessarily evidence against the local character of OQM, but they might also be an indication in favour of retrocausality. De Broglie, who was de Beauregard's professor, was against these ideas to the point of prohibiting him to publish them, until he reconsidered it when Feynman proposed that there are states running backward in time in his work about the positron (see (Price, 2008, p. 753, n. 3)). Even though Bell's work came later, de Beauregard's idea applies to his work as well. It is in this context in which it has been recently developed by a philosophical movement, initiated and promoted by Huw Price. We introduced the non-locality problem of OQM in terms of the difficulties in explaining the correlations between measurements performed on two entangled systems at spacelike separation. The idea suggested by de Beauregard is that if the state of the systems (or the additional variables) causally depend on the settings of the measuring device that are located within their future light cones, then the non-local correlations can be easily explained in a way compatible with the relativistic spacetime structure. As Price and Wharton (2015b, p. 2) put it: "The argument for action-at-a-distance assumes that quantum particles don't know what measurements they are going to encounter in the future. A little more technically, it assumes that the state of a particle before a measurement is independent of the particular setting chosen for that measurement (the choice whether to measure position or momentum, say." This amounts to a violation of measurement independence, also called statistical independence, the condition that was hidden in the first years of the development of Bell's theorem, and was discussed in by Shimony, Horne and Clauser their exchange on local beables with Bell, see (Bell et al., 1985). This condition, which is violated by retrocausal approaches to quantum mechanics, is stated as follows:

$$\rho_{a,b}(\lambda) = \rho(\lambda) \tag{12}$$

Or, analogously,

$$pr(\lambda|a,b) = pr(\lambda) \tag{13}$$

In words, the measurement independence condition maintains that the λs of the system are 'statistically' independent from the settings of the measuring device. In the retrocausal context, the λs are correlated with the settings, a and b which maintain their status of free variables – i.e., they can be chosen by the experimenters at will – since the act of setting the variables has an effect backward in time. Thus, "the measurement settings cause the incoming particle to have certain properties, just as the stone caused the window to break. The only difference is that in this case, down at the microscopic level, some of the causation works backwards" (Price and Wharton, 2015b, p. 4). If such a dependence is physically real, then Bell's theorem does not force us to accept that quantum mechanics is non-local. In other terms, a theory in which the settings have effects backward in time can be local and may be able to reproduce the predictions of quantum mechanics.

Retrocausal approaches to quantum mechanics are not the only kind of views about the theory that posit a violation of measurement independence. Superdeterminism is another alternative, which maintains that this condition is violated by the existence of a common cause that correlates the settings of the measuring devices with the λs. The common cause lies in the common region of the past light cone of the λs, a and b, making the spacelike correlations just apparent (under the non-consideration of the common cause). This view is typically dismissed because it is considered a case against free will and the the faithfulness of science. For example, Shimony, Clauser and Horne, who first explicitly identified the assumption had the following to say in (Bell et al., 1985, p. 101) about its status:

> In any scientific experiment in which two or more variables are supposed to be randomly selected, one can always conjecture that some factor in the overlap of the backward light cones has controlled the presumably random choices. But, we maintain, skepticism of this sort will essentially dismiss all results of scientific experimentation. Unless we proceed under the assumption that hidden conspiracies of this sort do not occur, we have abandoned in advance the whole enterprise of discovering the laws of nature by experimentation.

This view that considered superdeterminism as a conspiracy incompatible with the free will of the experimenters was popular (and perhaps it still is), but more careful analysis has shown that those alleged features are overstated. In what follows, our present study is concerned with the retrocausal approach, so that a review of the reasons why superdeterminism should not be considered as unscientific and a case against the free will of human kind is beyond our scope. The relevant point is that, as Price and Wharton (2015b) clearly explain, it seems to be an uncontroversial issue that the retrocausal approach, unlike the superdeterministic one, does not violate either the free will assumption nor is it an unscientific idea (as de Broglie himself believed until Feynman introduced states evolving backwards in time).[14]

Bearing this in mind, we can recognise the aims of the retrocausal approaches: by violating the measurement independence condition, Bell's theorem does not force us

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[14] For a contemporary discussion about the superdeterministic approaches see (Lewis, 2006), (Hermens, 2019), (Chen, 2020), and (Hossenfelder and Palmer, 2020).

to accept that quantum mechanics is non-local. Every physical event that appears in the correlations lies within the future and past light cones of the relevant beables. Thus, quantum mechanics is compatible with the structure of Minkowski spacetime. Now, there are several models that implement retrocausality. As it is recognised by Price and Wharton (2015b), the Parisian zig-zag, proposed by de Beauregard has been one of the most important. The proposal is based on the idea that the settings on one wing of an EPR-type experiment *affect* the correlated particle at spacelike separated wing, but not directly: the settings at the R-wing have an effect towards its backward light cone up to the source of the particles, correlating in this way the settings of the R-wing with the outcomes of the L-wing *via a zigzag* (see, for instance, (Price and Wharton, 2015a)). In conclusion, this strategy violates parameter independence between the two distant settings, although in a way that is compatible with Minkowski's spacetime structure.

There are different conceptions of retrocausality in physics and quantum mechanics (see (Friederich and Evans, 2019), although the most developed one is Price's Helsinki model, which was proposed in (Price, 2008), giving continuity to the ideas developed in his book (Price, 1996). It is important to notice that retrocausal models are not equivalent to models in which causation runs in reversal: causation in reversal takes place when we run the whole model in reverse. In any time-symmetric model this is trivial: if we swap the initial and final conditions, then what in the *original* model were the final conditions are now the initial ones (see (Price, 1996, p. 190)). Doing this does not change any characteristic of the model, since the laws it instantiate are blind to whether they run forward or backward in time. Thus, the direction in which we read causal relations is a convention.[15] Borrowing from (Price, 2008, p. 755), "since the direction of time is put in by hand, we could put it in 'backwards.'" Reverse causation happens when we change the initial conditions (or preparations) for the final conditions (or measurements), and the whole process represented by the model happens backwards, so that every causal process runs in the same direction (usually intrinsically linked to the direction of time in which the process takes place).

Unlike reverse causation, retrocausality or backward causation (which we take to be synonyms) refer to a causal relation that occurs in the opposite time direction with respect to the time direction of the model. That is, retrocausal correlations take place when, for instance, differences on the variables in the final conditions, $t' > t$ have effects on events or processes at $t < t'$. Despite that the direction of the model, which is put by hand, runs from t to t', there are causal correlations or processes running from t' to t. As Price (2008, p. 755) seems to say, in these cases retrocausality is not

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[15] Notice, however, that if we adopt an asymmetric notion of causation, once the causal arrow for the model is set, then a time reversal transformation does not change causes for effects. Swapping causes and effects gives rise to a new physical situation. See (Farr, 2020).

put in by hand in the sense that it takes place in the opposite time direction we choose to run the model. We shall consider causation, and therefore retrocausation as well, as an asymmetric relation which is not put in by hand nor is attached to a direction of time. Whilst the model is time-symmetric, the causal relations are not. Due to this asymmetry, causality has sometimes been dismissed in the philosophy of physics: the argument is that such an asymmetry is incompatible with the time symmetry of physical laws. We will not enter in this specific debate, although we believe, with Frisch (2014), that the incompatibility is only apparent, and the consideration of both causality *and* retrocausality removes the apparent difficulties.[16]

As a final comment we need to point out that, in what follows of this study, we will be victims of a confusing puzzle. Our *parlance* is constructed in a tensed way, and we cannot avoid talking about past, present, and future events in one way or another. As Dainton (2016, sec.3.3-3.6) explains, the structure of our language has always been a source of confusion and counter-arguments for the block universe perspective. Philosophers of language, including Russell (1915), tried to reduce the meaning of tensed statements to tenseless ones. For different reasons (see (Dainton, 2016)), the project failed. Luckily, we do not need to enter into this discussion, although we are going to face the inconveniences.

In the next section, we shall focus on Price (2012) and Price and Wharton (2017) argument defending that, under certain assumptions, retrocausality is not only an interesting approach to avoid the EPR-Bell non-locality, but it is required to be retrocausal (if quantum mechanics is time-symmetric and discrete). We believe that, with this, the theoretical status attributed to retrocausality has changed. We have seen how retrocausality can be employed in order to explain the violations of Bell inequalities respecting the structure of Minkowski spacetime. In this context, retrocausality can be seen just as an inference to the best explanation: if we believe in the structure of relativistic spacetime, it offers the best single-world-realist explanation for the violation of Bell inequalities. As we shall see, in (Price, 2012) and (Price and Wharton, 2017) the strategy is different. The argument does not aim to show that positing retrocausal effects explain some quantum phenomena, but rather that they are *required* by quantum theories that meet some characteristics. As it is going to become clear in due course, Price's conclusion is rather narrow since his assumptions apply to theories meeting very specific characteristics (i.e., realism, discreteness and time symmetry). Nevertheless, Leifer and Pusey (2017) claim to have made a challenging generalization of the results. The idea is that, under certain conditions, time-symmetric quantum models require backward causation, so that, granting the conditions, we need either to give up a time symmetry assumption or accept that the future affects the past by means of retrocausality (in the same way as the past

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[16] See specially (Frisch, 2014, chap.5).

affects the future). Whilst we present the arguments proposed by Price (2012), Price and Wharton (2017), and Leifer and Pusey (2017) we will critically discuss their assumptions, and we shall argue that there are interesting options left open by the discussion. Regarding the general research question of our study, this analysis will shed light on whether we should include retrocausality on the characteristics that a quantum theory compatible with the block universe ought to meet.

3.1 Price's retrocausal model for quantum mechanics

So far we have seen that, if quantum mechanics meets the measurement independence assumption, it implies non-local correlations between spacelike separated events. This statistical interdependence can be understood as implying action-at-a-distance or global correlations along the spatial dimensions. Measurement independence is usually assumed since its violation would imply features that are considered extravagant in the field, as for instance superdeterminism or retrocausality. But what if we live in a block universe in which phenomena do not have a fundamental and preferred time orientation? In this scenario, would be so extraordinary the existence of events that depend on other events lying both in their future and past light cones? Does the block universe perspective, which is often taken as suggested by special relativity, provide us with a smooth explanation of the spacelike correlations exhibited by quantum mechanics? Apart from the impossibility to identify presentness as a distinctive property, the standard characterization of the block universe perspective lies in the time symmetry of the fundamental laws. Thus, in order to analyse how the block perspective may help with our understanding of quantum mechanics, we shall have a look at time-symmetric quantum theories.

It is precisely here where things become even more interesting. Price (2012) and Price and Wharton (2017), argue that, under certain assumptions, time-symmetric quantum mechanics *requires* retrocausality. Tying up the ideas we have been discussing, the argument maintains that quantum mechanics in the block universe would require a violation of measurement independence. This seems to show that the block universe perspective would provide a powerful explanation about why quantum mechanics violates the (spacelike) Bell inequalities, although it is still local and can be reconciled with special relativity. Nevertheless, this comes at a price: accepting that some elements of reality depend on events lying in their future and past light cones.

After discussing Price's setup, we shall delve into the proposal of Leifer and Pusey (2017), which generalises the previous argument to render it applicable to a wider range of theories. There is, however, an assumption of both Price's setup and Leifer and Pusey's theorem, that has already been disputed by Adlam (2018b), namely, that every temporal correlation should be explained by an ontic state that mediates between them. The rejection of such an assumption, would lead to an approach in which

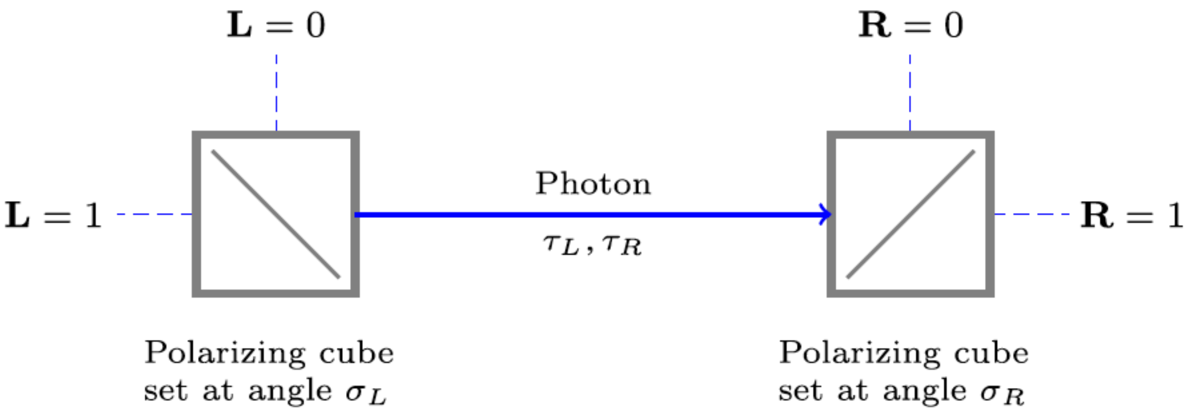

Figure 1: Price (2012, p. 77)

the entire history of events are determined 'all-at-once', in a way that seems to involve 'spooky-action-at-temporal-distance'. In 3.3, we discuss this approach and propose that time-symmetric quantum mechanics, that is, the quantum theories compatible with the block universe perspective, do not exhibit either retrocausality, nor action-at-temporal-distance, but fundamental temporal global correlations. These temporal global correlations would be analogue to the spatial global correlations defended by Myrvold, following the Shimonian tradition (see 2.3).

Whether quantum mechanics is time-symmetric depends on how we interpret it.[17] In this thesis we are concerned with what would be the consequences *if* some quantum theories are time-symmetric. Price holds that *if* that is the case, then we need to accept that there is retrocausality. In order to defend this claim, he proposes a thought experiment of two polarising cubes, where one is a mirror image of the other, representing a reversed process (see Figure 1). Then, he asks: is it possible to explain the correlations between incoming and outcoming photons in a two-polarising-cubes model with a time-symmetric dynamics and a realist ontology without requiring retrocausality? The answer provided is that, under an additional assumption, which is discreteness, retrocausality is indeed implied by the *dynamics*. In this context, retrocausality is understood in an interventionist sense: manipulations over inputs constrain the probabilities or affect the states of the systems in their past.
Price proposes three assumptions:

PI Discreteness: the model does not allow the existence of superposition. The photons can enter *and* emerge only from one channel of the polarising cubes at

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[17] As we will see, also the very definition of time symmetry is not a straightforward issue.

a time. Within the variety of interpretations of quantum mechanics, this means that there are single definite outcomes, there are no empty waves – in the case of dBB – nor many-worlds. If we take, for instance, OQM and dynamical collapse theories, and we consider the polarisers as measurements, then the outcoming photons are discrete (and, by time symmetry, the incoming photos would have to be discrete as well).

PII Realism: there are quantum states, and they explain the correlations between the cubes. These states carry information, for instance, about which is the polarization angle and the input channel they entered, from one cube to the other. This assumption is taken as a strong reason of why we should take events happening on one wing as constraining and providing information about events taking place at the other wing. It involves realism about the wave-function or the quantum state as an ontological mediator between the cubes. In other words, they are taking the quantum state after the first polarising cube as a *beable* (see (Price, 2012, p. 78)).

PIII Time symmetry: “if a process is permitted by the theory, then so, equally, is the process we describe by replacing t by $-t$ in a description of the original process - by ‘playing the video in verse,’ in the familiar analogy” (Price, 2012, p. 78). The crucial idea in this condition is that we should not be able to individuate a preferred time direction in which the model is being run.

Let us analyse the polarization model for quantised photons, which consists in two polarising cubes with two input channels and one output channel each. See 1. The right poliriser is conceived as a reversal of the left one. If we arrange the R-cube as being a mirror reflection of the L-cube, then one side has two input channels, let's say $L = 0$ and $L = 1$, with one output τ_L, determined by the input channel and a polarisation angle σ_L; and the other has two output channels, R=0 and R=1, with one input channel (towards which τ_L is directed), and a polariser σ_R. Each cube consists in a wing of the experiment, the L- and R- wing, where there are experimenters that control the polarisation angle, σ_L and σ_R, respectively. We can also call the L-cube, the preparation cube, and the R-cube the measurement cube. Let's assume that there is a temporal interval between a photon entering through one of the cubes, let's say the preparation cube, and being redirected with a given polarisation angle to the the measurement cube, so these are sequences of events. By PIII, the sequence of events can be reversed without having any change neither on the experiment nor in the probabilistic expectations. So far, the setup is not time-symmetric since the L-experimenter is able to decide whether to introduce the photons either on the $L = 0$ or the $L = 1$ channel, *and* how to set σ_L. In contrast, the R-experimenter has control only over σ_R, and not over where the particle is actually found at the end of the experiment, either $R = 0$ or $R = 1$. Paraphrasing Price and Wharton (2017, p. 123), which channel the photon comes out of is controlled by Nature and not by us. The impossibility of the R-experimenter to decide from which channel the photon emerges is due to PI. If the photon could emerge from both channels at the same time in different proportion, that is, if the photon can be found in a superposition of $R = 0$ and $R = 1$, then the R-experiment would be able to decide the output.[18]

As a result, the L-experimenter has more control than the R-experimenter. This additional control is not trivial since it enables them to signal towards the R-wing. Notice that, if time symmetry is an assumption consisting in the impossibility of telling the direction in which the model is running, then just changing the control from the L-cube to the R-cube in a time-reversal experiment would not work. The time symmetry assumption under consideration requires that, without 'changing the description of the original process' – which includes the operational control in each wing – a time-reversal transformation should leave invariant the phenomenon, so that it is not possible to establish a particular time-direction. Swapping the asymmetric control from one wing to the other is, clearly, a change in the description of the original process, and thus in the model. In any case, if we can establish an asymmetric arrow of signalling, then we can say that the model is time-directed, breaking the time symmetry required since there would be statistical dependencies showing up only in one time-orientation.

The reader may feel that the adopted notion of time symmetry is inappropriate or too strong. But there is a clear motivation behind it. The fundamental time symmetry in question has to be one compatible with the block universe perspective. If a time-reversed experiment consists in swapping the control between the wings, so that the arrow of signalling changes from one direction to the other, then we can still individuate a temporal arrow. This would only show that the direction of the temporal arrow is conventional, but not that there is no difference between past and future. In fact, it is usually recognised that the arrow of thermodynamics is of this kind: it does not matter if it runs from past to future or future to past, as long as it consists in a time-directed gradient (see (Price, 1996)).

The arrow of signalling may be associated with a thermodynamic arrow of time, since it depends on what agents can control (and their own arrow of time, which is often taken to be a thermodynamic arrow). Applying this to our setup, this asymmetry is due to an asymmetry between the initial and final condition. In order to solve it, it is needed to symmetrise them. Thus, in order to see the consequences of PIII for quantum mechanics, it is also needed to operationally symmetrise the control over the cubes that the experimenter of each wing has. For this reason, Price introduces

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[18] The same reason applies for the classical level, although changing superposition by intensities. The relevant factor is the continuity over the different values, which is denied by PI.

the ‘Demon on the left’, a conceptual tool to restrict the control on the L-wing to signal towards the R-wing. The Demon on the left symmetrises the experiment; it is no longer possible to signal either past-future nor future-past since he has the control over which channel the photons are introduced. As Price (2012) says, the Demon plays the role that ‘Nature’ has over the end of the experiment, where the photons go out. The result is that both experimenters have now symmetric control. Considering that we do not expect to be able to signal from the future to the past, the natural solution for the symmetrisation is not giving up PI, but constraining the control over the L-wing.

Does the introduction of the Demon deprive the experimenters of all the control? Absolutely not. Due to PI, the restriction over the experimenters’ control induced by the Demon is not total: they still can constrain the probability amplitudes of $\tau : L$ up to an additive factor of $\pi/2$. More precisely, τ_L can take only two values; either $\tau = \sigma_L$, if the Demon uses $L = 1$; or $\tau = \sigma_L + 90$, if the Demon uses $L = 0$. This means that the experimenter can constrain the state of the system in $90^{\underline{\text{o}}}$. Once again, this is explained by an asymmetry, this time between the difference in the control that the Demon/Nature and the experimenters have. Whilst the Demon/Nature have just two *discrete* alternatives to choose, the polariser knob setting remains continuous, that is, it can be set in any degree. Note that if the Demon/Nature had continuous control, they would be able to counter every choice made by the experimenters.[19]

Careful consideration of this shall show us that the symmetrisation of the initial and final conditions is not enough to guarantee that the model is time-symmetric. In its current state, the model exhibits a crucial feature that allows us to to distinguish the time-direction in which the experiment is being performed. The key here is PII, that is, the assumption that the photon that mediates between the two cubes is a *beable* of the theory that explains some features of the model. This photon is correlated with the polarization cube it went through first. Remember that τ_L is the photon coming from the L-cube, and consequently, it is correlated with σ_L. In the time-reversed experiment, it would have not gone through σ_L, but σ_R. Theoretically, this would be enough for a third experimenter, analysing the entire setup, to discern in which direction the model is being run. If they find that the photon is correlated with σ_L, then there is a fact of the matter that it passed through the L-cube at, say, t_1, and is going to come out by the R-cube at t_2. If it is polarised in the same direction as σ_R, then the events at the R-cube took place before the events at the L-cube. These two physical situations would be different, and theoretically distinguishable, enabling the experimenters to identify the time’s arrow of the model. Note again, the issue is not only that both results are allowed by the theory (in the same form as it does

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[19] More about the consequence on the asymmetry of control and the difference continuity would make can be found in (Price and Wharton, 2017, p. 132).

not really matter weather we consider that increases wither towards t or towards $-t$), but rather that they do not pick a preferred direction in time. In a nutshell, such a model would not meet the time symmetry condition we are interested in.

At this point, we can appreciate that the conjunction of the three assumptions requires that, if there is a *beable*, τ_L, which is partially constrained by the L-experimenter, there must to be another beable, τ_R, with the same status as the former, travelling from the R-wing to the L-wing. As Price (2012, p. 78) puts it: "time-symmetry thus requires that there is an element of reality, τ_R, that stands to σ_R, $R = 1$ and $R = 0$ in precisely the way that τ_L stands to σ_L, $L = 1$ and $L = 0$." *If* we give a beable's status to τ_L but we do not give it to τ_R, then we would be able to theoretically discern whether a film of the experiment is running forwards or backwards in time, and *hence* it would violate PIII. To sum up, if we want PIII, we should not be able to discriminate any difference between the forward and backward experiment. For this, it is necessary to give τ_R a beable status, and deem that the R-experimenter has the same control over τ_R as the L-experimenter over τ_L. In a nutshell, whatever is happening in between the two polarisers has to be correlated with both the L-wing and the R-wing, and a consequence of PII is that such correlations should be explained, in some way, by the quantum states.

In an interventionist account of causation, this implies that either τ_L or τ_R should be considered as a retrocausal effect. Which of them is considered as *the retrocausal one* is a matter of convention; the relevant point is that these two *beables* are running in opposite time directions. In a manipulability account of causation, involving epistemic agents, which is the standard causal effect and which the retrocausal one is relative to the arrow of time introduced by the agents. In such a perspective, retrocausal effects are those that affect the own past of the agents. Moreover, in this account, the asymmetry of causation is due to the temporal arrow of the agents. Price adopts the latter alternative (see (Price, 1996, p. 157)).

To make it clear, the manipulation of the L-experimenter over σ_L is a causal element, up to an additive factor of $\pi/2$, of the resulting beable τ_L. The same has to occur, then, in the R-wing: the manipulation of the R-experimenter over σ_R is a causal factor, up to an additive factor of $\pi/2$, of the resulting beable τ_R. There is one difference, though. If we take the original description of the experiment, with its corresponding sequence of events (where the Demon introduces a photon in one channel of the L-cube, the experimenter wiggles σ_L, and then a beable produced and directed towards the R-cube), the manipulation of the settings has an effect forward in time. Relative to this description, the manipulation changes the state of the beable *after* the manipulation has taken place since the polarisation of the photon is correlated to σ_L . Conversely, taking into consideration the same description of events, we observe that in the case of the R-wing, the manipulation of the settings has an effect backwards in time. Wiggling the polariser σ_R to any amount $\rho \neq \pi/2$

has a retrocausal effect over the (previous) state τ_R. "In counterfactual terms, it seems reasonable to say of any particular case that if she had chosen $\sigma_R + \rho$ rather than σ_R, the value of τ_R would have been different" (Price, 2012, p. 78). The parameters of the R-wing are correlated *backward* in time with the polarisation of the photon. This polarised state evolving backwards from the R-wing, which following PIII and PII should be a beable, is a *retrocausal state*. In sum, relative to the original description, the R-experimenter has *backwards* control over τ_R, $mod \pi/2$ (just as the L-experimenter has over τ_L). Another way of seeing this is that the state of the photon in between the cubes, coming from the L-cube towards the R-cube, *knows* the setting that the R-experimenter would choose. But again, and this is a very important element for what follows, given PII, the photon cannot just *know* the setting without a physical influence that *tells* it the information.

Let us conclude this section with a minor remark: retrocausality is needed in this model because of PI. If it were possible that the photon went out from the R-cube in a superposition of $R = 0$ and $R = 1$ states, then manipulating the polariser of the same cube would have an effect forward over the superposed state (in the proportion in which it would be in $R = 0$ and $R = 1$). But then, why people that is sceptic about retrocausality should assume PI? In fact, two of the mainstream interpretations, among the philosophy of physics community, of quantum mechanics deny this assumption, namely the dBB and the Everettian interpretations. According to (Price, 2012, p. 78), "the real interest of Discreteness in the quantum case stems from the fact that it does turn out to be a realistic restriction, at least under some views of quantum ontology, at the other end of the experiment [that is, in R=1/R=2]." Discreteness is interesting since we never observe states in superposition, but always having a definite value. When we measure the position of the outcoming photon, we will always see it either on, say, $R = 1$ or $R = 0$; never being in a superposition of coming out by both channels. This issue is intrinsically related to the measurement problem, which we explain in 4.1. There, we shall consider how collapse theories solve this famous puzzle of quantum mechanics, and how a flash ontology can be used to build a time-symmetric and discrete theory.

3.2 Leifer and Pusey's retrocausality theorem

In this thesis, we have seen that Bell generalised the EPR argument by means of a theorem that is independent of the features of the specific interpretations of quantum mechanics.[20] Thus, if the assumptions hold, then we shall recognise that quantum mechanics displays some kind of non-locality (usually understood as the negation of the local causality condition). Leifer and Pusey (2017) aim to generalise Price's

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[20] Arguably, the derivation of Bell inequalities does not depend on quantum mechanics.

argument in a way similar to what Bell did with EPR. They consider that Price's assumptions are too restrictive, so that they reconstruct the argument in the form of a theorem, which we call the retrocausality theorem, that applies to theories that do not need to be realist about the quantum state, nor discrete. Thus, the conclusion of the theorem is slightly different: given some typical realist assumptions, unless we accept retrocausality, time symmetry is incompatible with the predictions of quantum mechanics. In other words, a time-symmetric theory that is not retrocausal imply a temporal analogue of Bell inequalities that are violated by quantum mechanics. We shall see that despite Leifer and Pusey's aims, the conditions under which the retrocausality theorem holds are still very specific, and some of them controversial. Given this, we propose a competing interpretation of the theorem. We argue that, although it does not compel us to accept *retrocausality*, it *does* show us a relevant lesson: if time-symmetric quantum theories do not imply retrocausality, they still exhibit (fundamental) temporal global correlations. These temporal global correlations point out to the fact that there are non-trivial dependencies between future and past events. Our interpretation of the retrocausality theorem is analogous to Myrvold's interpretation of Bell's theorem (see 2.3). In 4, we reinforce our argument by an analysis of time-symmetric collapse models.

An important difference between retrocausality and temporal global correlations is that while the former entails a violation of measurement independence, the latter does not. This turns out to be crucial for our general research question since, if time-symmetric quantum mechanics implies retrocausality, then quantum mechanics in the block universe provides a smooth local explanation of the violation of Bell inequalities. As a consequence, we would have a strong reconciliation between quantum mechanics and special relativity by means of a hypothesis about the ontological structure of events in spacetime. Nevertheless, if time-symmetric quantum mechanics implies temporal global correlations, measurement independence is not necessarily violated and whether we get a local explanation for the violation of Bell inequalities becomes dubious.

3.2.1 The preparation-measurement model and the assumptions of the retrocausality theorem

The setting of the retrocausality theorem is similar to that in Price's argument. For the sake of consistency with Leifer and Pusey (2017), we shall re-label the L- and R-wing by preparation and measurement. The main apparent difference between the two models is that Leifer and Pusey (2017) introduce a third cube in the middle, which represents a transformation happening between the preparation and measurement. As recognised by Leifer (2017, p. 4) in a reply to some criticism made by Maudlin (2017), the transformation does not play any role in the argument, so we shall omit it. The role of the transformation cube was only to make the preparation-(transformation)-measurement model similar to Bell's setup, which has three elements as well: the preparation and two measurement wings (see (Leifer, 2017, p. 4)).

Consider two cubes, one representing the preparation and the other the measurement. Like in Price's model, the idea is that they are the reverse of each other; which one is the preparation and which one is the measurement can swap. Each of these cubes has a controllable and an uncontrollable variable associated with inputs and outputs. Although it is assumed that the input is set before the output, their distinction does not depend on a time-order, but on their being controllable or uncontrollable. This means that the description of the model defines what is controllable and what is not so that the distinction is not based on what is *in principle* controllable and uncontrollable. The case is similar in Price's setup: the Demon/Nature are the uncontrollable variables, and the angles of the polarisers are the controllable ones; the former are the outputs and the latter the inputs. It is important to bear in mind right from the start that a time-reversal transformation does not change what is controllable and uncontrollable, and hence it does not shift inputs for outputs.

We consider an *operational theory* for this setup, consisting in the specification of a triple (P, M, T). This means that the theory defines a set of possible preparations, $\mathcal{P}$, a set of possible measurements, $\mathcal{M}$, and a set of transformations, $\mathcal{T}$. In accordance with what we just said, the preparations and the measurements have an input, X, and Y, and produce an output A, and B. A and B are random variables taking values, a and b, over a defined finite set Ω_A and Ω_B, whilst X and Y, are free variables taking values, x and y, in Ω_x, and Ω_y. An experiment is defined as a (P, M, T), with a $\mathcal{P}$, $\mathcal{M}$, and $\mathcal{T}$ compatible with each other. The preparation, transformation and measurement "can be performed sequentially in time on the same system" (Leifer, 2017, p. 4). This last characteristic enables us to relate the model with time symmetries.

The theory needs to define a probability distribution over the outputs A, and B, given specific values for the inputs, $X = x$ and $Y = y$, respectively. Formally, given an experiment (P, T, M), the theory has to provide predictions for the probabilities $pr_{PTM}(A = a, B = b|X = x, Y = y)$ for every $a \in \Omega_A$, $b \in \Omega_B$, given any $x \in \Omega_X$, and $y \in \Omega_Y$. Without further remarks, let's see how this model applies to quantum mechanics, as it is expressed by the (Leifer and Pusey, 2017, p. 6):

> ... In quantum theory, a preparation P is associated with a Hilbert space $\mathscr{H}_A$, a set of (unnormalized) density operators $\{\rho_{aA|x}\}$ on $\mathscr{H}_A$ - one for each choice of x and a - such that the ensemble average density operators $\rho_{A|x} = \sum_a \rho_{aA|x}$ are normalized $Tr(\rho_{A|x}) = 1$. The preparation procedure starts with the experimenter choosing x. The preparation device then generates a classical variable a with probability distribution $p(a|x) = Tr(\rho_{aA|x})$, outputs a and prepares the system in the corresponding (normalized) state

$\rho_{aA|x}/p(a|x)$, which is subsequently fed into the transformation device. A measurement M is described by a set $\{E_{b|yB}\}$ of positive operator-valued (POVMs) on a Hilbert space $\mathscr{H}_B$ - one POVM for each choice of y. This means that for each (y, b), $E_{b|yB}$ is a positive operator, and for all y, $\sum_b E_{b|yB} = I_B$, where I_B is the identity operator on $\mathscr{H}_B$.

Given this characterisation, the Born rule dictates that the probabilities for this experiment are given by

$$pr_{PMT}(A = a, B = b|X = x, Y = y) = Tr(E_{b|y}\rho_{a|x}). \tag{14}$$

This model is charged with five assumptions:

LPI Single world realism

LPII λ-mediation

LPIII **Time symmetry**

LPIV Free choice

LPV No-retrocausality

Briefly, LPI states that to every system in the model is ascribed an ontic state, which represents definite physical properties. Thus, the ontic state gives a probability distribution over possible measurement outcomes. LPII is very important for our research; it says that every correlation between preparations and measurements are mediated by the ontic state of the system. As we shall see in detail, this means that the model is temporally local and satisfies the Markov condition. LPIII is crucial, but problematic, maintaining that the operational time symmetries of the quantum formalism must be explained by underlying ontological time symmetries. As Leifer and Pusey (2017, p. 16) recognise, this assumption is equivalent to the conjunction of PI *and* PIII: "...our **Time symmetry** assumption plays an equivalent role to the conjunction of *Discreteness* and *Time symmetry* in Price's argument." Consequently, if it is deemed pertinent, instead of LPIII, we can consider {PI + PIII} to explore the implications of the theorem. Taking into consideration some reasons that we are explaining in due course, we shall investigate the alternative of using {PI + PIII} rather than LPIII, specially in 4.5, where we apply the theorem to time-symmetric collapse models. We call the theorem, after this revision, the modified retrocausality theorem.[21] LPIV claims that the settings of the model, i.e., the controllable variables, are free external variables. LPV establishes that the uncontrollable variables are statistically independent of any controllable variable lying in their future. In other words, causation runs only in one temporal direction of the model and the measurement independence condition is met. *The* direction in which causation runs might be a matter of convention; the key is that there are not two causal arrows in opposite directions.

The retrocausality theorem proves that any operational theory meeting the assumptions generates predictions that are inconsistent with the expectation values of quantum mechanics. In other terms, the joint assertion of LPI-LPV entails a timelike analogue of Bell inequalities for the spatial case, so that we are compelled to give up one of the assumptions. The authors consider that LPI, LPII and LPIV are essential for *any* realist theory, and hence they discard them as options to give up. Therefore, the argument goes, we should decide between rejecting LPIII and LPIV. The former seems to be a fundamental characteristic of physics, so the authors invite us to give up LPV. Accepting this, the conclusion becomes: *time-symmetric quantum models require retrocausality, otherwise they are incompatible with quantum mechanics.*

Taking now into account the general narrative of our thesis, which is, remember, studying the characteristics of quantum theories in the block universe perspective, we should conclude that, *if* fundamental time symmetry is an indispensable characteristic of the block universe, then, by the retrocausality theorem, the quantum theories compatible with this perspective must be retrocausal. We shall recognise that, on one hand, this may be a problem for this view about the nature of spacetime since it demands characteristics that are considered extravagant by some people in the field, namely, that there is retrocausality. On the other hand, the block universe would solve at once the problem of explaining the results of Bell's theorem in a way that Minkowski spacetime is fully respected. Before delving into these issues, let us give a detailed and critical account of Leifer and Pusey's theorem.

3.2.2 Discussion of the assumptions

In this section, we shall comment on the assumptions of the retrocausality theorem. As we will see, a detailed account of them will be essential to apply the modified retrocausality theorem to collapse models in 4.5.

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[21] It is relevant to notice that, by employing the conjunction of PI and PIII instead of LPIII, we are not giving up Leifer and Pusey's retrocausality theorem. While Price's setup consists in a toy-model, the retrocausality theorem involves other assumptions besides LPIII that are not captured by Price's model. Moreover, the retrocausality theorem involves the derivation of a contradiction with quantum mechanics, which is absent in Price's argument. As Leifer and Pusey (2017, p. 16) explicitly mention, this contradiction can be derived by means of PI + PIII –plus the extra assumptions– as well. In other words, the contradiction can be derived from the modified retrocausality theorem.

LPI : to every physical system in the model is attributed an ontic state, λ, representing the physical properties that the system can take. The different possible values that λ can take form a set Λ. The ontic state may not be known, but it has always definite values which are, in principle, knowable. In other words, this means that the *ontic state* is a *beable* of the model. Together with LPII, this assumption involves realism *à la* Einstein and Bell. It is for this reason that, as it is usually the case, these retrocausal frameworks have in mind Additional Variables Theories, in which there is a quantum state which is supplied by additional variables. The general aim of retrocausal approaches is to render these additional variable theories elude the consequences of Bell's theorem, which can be interpreted as a no-go theorem for local hidden variable theories.

An ontic extension of a theory is an specification of an ontic state space Λ together with the a conditional probability distribution of possible outcomes, given a specific parameter (see (Leifer and Pusey, 2017, p. 9).

LPII : this is the second horn of the realist assumption. Whilst LPI maintains the existence of ontic states, λs, LPII claims that those ontic states should mediate and explain *every* statistical correlation between variables that is not screened-off by a common cause. This connection is conceived as a physical link generated by the ontic state λ: "... any correlation between a preparation and a measurement made on a system should be mediated by the physical properties of the system" (Leifer and Pusey, 2017, p. 2). The central idea in our timelike scenario is that every correlation should be explained by physical properties evolving over time, which are taken as information carriers. The ontic state at a given moment gives maximal information about the following state. More precisely, given a sequence of states λ_1, λ_2, and λ_3, taking place at t_1, t_2, and t_3, the ontic state λ_2 screens off any possible correlation between λ_1, and λ_3 (see (Leifer and Pusey, 2017, p. 11)). Applied to the model, the condition implies that the correlation between the preparation and the measurement is screened off by the intermediate state between them. That is, conditioning on the ontic state at t_2, renders irrelevant the ontic state at the moment of the preparation, t_1, for the state at the measurement, at t_3.

A key element of this condition is that in the timelike scenario it implies that the model is Markovian. The Markov condition means that an event is maximally determined by the state of the world previous to it. For example, if we measure a system, the outcome is maximally determined by its state at the moment immediately previous to the performance of the measurement. Because of this, a Markov process is said to be memoryless: every state of the system, previous to the actual one is irrelevant for the determination of the following state. The explanation for such a feature lies in λ-mediation. The state that mediates every correlation in time encodes all the relevant information from the history; once we condition on it, all the previous states become redundant. As Allori et al. (2008, p. 381, n. 15) put it, the Markov condition means that "P(future|past&present) = P(future|present)". This last formulation shows explicitly that the past and future are screened off by the state of the system at the present.

Another conceptualization of what this property adds to the model has been addressed by Adlam (2018b), who stresses that λ-mediation is a temporal locality condition. Thus, in a theory meeting this assumption, the correlations over time are mediated by the ontic states carrying the records of the past. In contradistinction, a theory that rejects this assumption is characterised by the author as exhibiting action-at-a-temporal-distance; a state of the world (or a system) at a given time is not maximally determined by the state of the world at precisely the previous instant, but rather by all the history of events. In other terms, the state of the world at t would be determined by many events on its time history that are not spatiotemporally contiguous to it, in a way that implies 'instantaneous' action-at-a-distance across the temporal dimension.

Before continuing we should superficially remark that unlike Leifer and Pusey, we do not consider that there are good reasons to maintain that this assumption is necessary for any realist model. After all, in the spacelike case, locality is not a requisite for a quantum theory to be considered as realist. Moreover, without entering into details, the very characterisation of what realism means is, in general, not straightforward. In the quantum case, it is even more ambiguous: does realism commit us to the reality of a wave function living in a multidimensional Hilbert space? Should we be realists also about the definite states we have empirical access to? Does realism imply that the ontic states *always* have definite values? These and other issues related with how realism in quantum mechanics could be understood are addressed by Maroney and Timpson (2014).[22] In a similar spirit, Adlam (2018b) defends that considering λ-mediation as an indispensable feature of any realist theory is becoming a risky dogma, with pragmatic, metaphysical, and historical motivations that are not always taken into deep consideration. As we shall show in 4.5, collapse models with flash ontology can be interpreted as realist models that reject this assumption.

LPIII : we must be able to infer ontological time symmetry from the operational time symmetry of a model. The idea is that "the most natural explanation for an operational time symmetry in a theory is that it is a reflection of an ontological time symmetry" (Leifer and Pusey, 2017, p. 12). As recognised by Leifer (2017), the formulation of this assumption is the most controversial issue of the retrocausality

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[22] To appreciate the complexity of the realism vs. anti-realism debate about quantum mechanics see (French and Saatsi, 2020) and references therein.

theorem. This is so since it says that the operational time symmetry displayed by a model should be taken as strong evidence in favour of an ontological time symmetry. Notice that the assumption is not supposed to be that a model is operational time-symmetric, but that this characteristic enables a justified ontological inference. Various comments are needed concerning this point.

Before taking into consideration the formal definition of operational and ontological time symmetry offered by the authors, we consider necessary a discussion of their broad view of time symmetry. From the beginning of the paper it is admitted that operational time symmetry is different from the standard view of time symmetry of dynamical laws. The authors claim that their notion is grounded, in first place, on the symmetry of the *formalism* of quantum mechanics. "The symmetry in question is that the retrodictive formalism is mathematically identical to the conventional predictive formalism" (Leifer and Pusey, 2017, p. 2). This characterisation, then, stresses that the application of the quantum algorithm to make prediction and retrodictions is exactly the same.

Following the authors, consider two polarisers r and l, the polarisation state of a photon that passes through l with certainty $|\psi_l>$, and the state of a photon that passes r with certainty $|\psi_r>$. As it is well know, the quantum algorithm tells us that, if we want to calculate the probability that the photon goes through r, having already gone through l we have to compute $|<\psi_r|\psi_l>|^2$. This is for predictions. For retrodictions, or a prediction relative to the time-reversed experiment, where we want to know the probabilities of the photon passing through l, after having passed through r, we calculate $|<\psi_l|\psi_r>|^2$. Both expressions give the same result, so they are in a sense equivalent. Leifer (2017, p. 3) shows that this can be generalised to n polarisers placed in sequence. Let's consider $|\psi_j>$ the state of the photon that passes the j^{th} polariser with certainty. The joint probability that, after passing the first polariser, it passes 2,3,...,n is $\prod_{j=1}^{n-1}|<\psi_{j+1}|\psi_j>|^2$. In the time-reversed case, the probability of passing *n-1*, *n-2*,...,1 given that the photon passed the n^{th} polariser is $\prod_{j=1}^{n-1}|<\psi_{j+1}|\psi_j>|^2$ as well. In synthesis, what the authors consider as the operational time symmetry of the formalism is explicitly motivated on this feature of the mathematical structure of predictions and retrodictions in quantum mechanics. But then, the authors need to add the notion of inputs and outputs of the preparations and measurements, as well as considering the issue of signalling. And with this, the direct relation with the formal property of the algorithm we have just seen becomes fuzzier.

After offering the prediction-retrodiction symmetry, and claiming that it motivates the usefulness of their operational notion of time symmetry, they proceed to define operational and ontological time symmetry by means of the slippery analogy about the impossibility to distinguish between a video being played forward or backward. The analogy might be good to give an intuitive and broad idea of time symmetries, but it does not cut the ice between the different conceptions available in the literature. More specifically, it does not help to distinguish between the dynamical and the operational time symmetries under consideration. Actually, this analogy is also successfully used to introduce the dynamical symmetries of physical laws, which are those that this proposal wants to leave aside.[23] Thus, they maintain that *operational time symmetry* refers to the impossibility to distinguish whether an actual video, that captures only the observable elements of the actual performance of an experiment, is being played forwards or backwards. *Ontological time symmetry* refers to the idea that a video is "merely a conceptual stand for the complete record of everything that exists" (Leifer and Pusey, 2017, p. 4). In both notions, the phenomenon has to be "equally *likely* in both time directions" (Leifer and Pusey, 2017, p. 5). The argument then states that an operational time symmetry *needs to be explained* by an ontological time symmetry. In other terms, the time symmetry of the observable elements of a video *justifies* us to infer a time symmetry about 'the record of everything that exists.' We believe that despite the pronouncements of the authors we can still ask: is this inference guaranteed?

Besides that these definitions do not help us to distinguish in a clear and precise way the dynamical symmetry from the operational one, we see another relevant issue: *the operational time symmetry is most of the times a construction.* Borrowing from (Leifer and Pusey, 2017, p. 5), "of course, the universe as a whole does not display such a time symmetry, and we will not be assuming that it does. However, it is possible to construct experiments that have this time-symmetry at the operational level." We consider that this inference is not properly justified. To be clear, the problem is that we are expected to infer from a constructed feature of the model a characteristic of the world, without further grounds. As we shall discuss in short, we consider that the operational time symmetry can be justified by means of the standard time symmetry of the fundamental laws of physics (and then, *maybe*, someone can make the ontological step), although this is not the strategy employed. It is rather dubious that Leifer and Pusey have this alternative at hands since it would imply reintroducing discreteness as a different assumption. The discreteness assumption would be needed in order to be able to take, for instance, a photon being detected at one port of a beamsplitter as the reverse of a photon entering to a beamsplitter by a definite port (otherwise, we will have asymmetric boundary conditions).

Let's see now if the technical definitions solve some of the problems that we pointed out, and what is the direct relation with the temporal asymmetry of signalling in quantum mechanics.

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[23] In fact, the same analogy is used also in (Price, 1996) and (Price, 2012) to characterise dynamical time symmetry.

Operational time symmetry: "an experiment (P, M, T) has an *operational time reverse* if there exists another experiment (P', M', T'), where P' has the same set of inputs and outputs as M, M' has the same set of inputs and outputs as P, and

$$pr_{P'M'T'}(b, a|y, x) = pr_{PMT}(a, b|x, y) \tag{15}$$

" (Leifer and Pusey, 2017, p. 6).

Ontological time symmetry: "in an ontic extension of an operational theory, the ontic extension (P, M, T, Λ) of an experiment (P, M, T) has an *ontological time reverse* if there exists another experiment (P', M', T'), with an ontic extension (P', M', T', Λ'), where P' has the same sets of inputs and outputs as M, M' has the same sets of inputs and outputs as P, there exists a one-to-one map $f : \Lambda \to \Lambda'$, and

$$pr_{P'M'T'}(b, a, f(\lambda)|y, x) = pr_{PMT}(a, b, \lambda|x, y) \tag{16}$$

" (Leifer and Pusey, 2017, p. 12).

As it is evident, operational time symmetry is defined in terms of the symmetry of controllable and uncontrollable variables of the preparation and measurement wings of an experiment.[24] To explain in words this symmetry, Leifer and Pusey (2017, p. 6) offer the following desideratum:

> for each run of an experiment, consider a record of inputs and outputs of the preparation and measurement (x, a, y, b). The experiment is repeated an arbitrary large number of times with each choice of inputs and the records are presented to a third party, without telling them what the preparation, measurement and transformation actually is. We also give them the same records with the order of preparation and measurement variables reversed (y, b, x, a). If knowing the theory, they cannot tell which is the true record and which is the reversed one, then the theory has operational time symmetry (our emphasis).

Let's come back to the question about whether these symmetries are found in nature. The authors stress again that nature does not display such symmetries; experiments of this kind are not generally operationally time-symmetric *because* there is an *asymmetry* between what is controllable and what is not controllable in the preparation-measurement cubes. As in Price's case, before the introduction of the Demon such asymmetry entails that we can signal in one direction (from what we call the past

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[24] Remember that the stipulated controllable and uncontrollable variables of the experiment are the inputs and outputs, and given that they are not intrinsically related with a time order, a time-reversal of the experiment does not entail a change between inputs and outputs.

toward what we call the future), *but not* in the other (i.e., we cannot signal from future to past). Operationally, this means that it is expected that the theory satisfies

$$\sum_b pr_{PMT}(a,b|x,y) = \sum_b pr_{PMT}(a,b|x,y'), \tag{17}$$

meaning that for every y and y' – i.e. the inputs of the measurement on the 'future' – there is no difference on the probability for $A = a$, – i.e. for specific preparation outcomes. In other words, the controllable variables of the measurement, meant to be in the 'future', cannot be used to signal to the preparation, which is on the 'past' of the measurement event. Nevertheless, we *do not* expect that the theory satisfies

$$\sum_a pr_{PMT}(a,b|x,y) = \sum_a pr_{PMT}(a,b|x',y), \tag{18}$$

for $x \neq x'$, since there is no problem if the output of the measurement give information about the input of the preparation, which is to say, that it is possible to signal to the 'future'. In brief, this happens if the input of the preparation makes a difference on the probability distribution of the measurement outputs (see (Leifer and Pusey, 2017, p. 7)). Experiments in which these two conditions are met are characterised as non-signalling: it is not possible to signal from future to past nor from past to future. This characteristic is an indispensable condition for operational time symmetry, since if it is not met, then we shall find statistical correlations *only* in one time direction, and we would be able to distinguish the direction that matches our time's arrow (that is, the time arrow in which signalling takes place towards the future). The question is, then, how to justify that the theorem only applies to the non-signalling sector of the theory, that is, to the sector in which measurements do not affect the probabilities of measurements at other times.

Now we reached a point that is crucial for our discussion. Nature does not display operational time symmetry, and when scientific models of experiments are built, the symmetrisation seems to be *put in by hand*. Thus, the authors claim: "an experimenter typically has more control over the preparation than the measurement, but there is reason to believe that this is an emergent, rather than fundamental, asymmetry... In order to identify the fundamental operational time symmetries, we want to factor out this emergent asymmetry in some way... For our purposes, it is sufficient to (instead) restrict the experimenter's control over the preparation procedure, so that she cannot send signals forwards in time. Doing this plays the same role as the 'demon on the left' in Price's argument" (Leifer and Pusey, 2017, p. 7). And, consequently, they justify the symmetrisation maintaining that: "we do not believe that the lack of operational time symmetry is a fundamental asymmetry of physics, but it is rather a consequence of the thermodynamic arrow of time" (Leifer and Pusey, 2017, p. 7).

Thus, the main rationale for the introduction of such a symmetrisation, which, again, *is taken as evidence for an ontological time symmetry*, lies in the fact that experiments are controlled and described by human beings. Human beings, the argument goes, introduce an emergent asymmetry due to the thermodynamic irreversibly.[25] We concur with the explanation about what is the source of the time asymmetry, but we believe that the justification of the symmetrisation of the model requires the acceptance of dynamical time symmetries. However, as the authors recognise, if we introduce the dynamical notion of time symmetry, then we need to find a way to block the counter examples of dBB and many worlds theories, which are dynamically time symmetric, but do not require retrocausality (see (Leifer and Pusey, 2017, p. 3)).

The argument does not seem congruent with their own view of operational time symmetry and its priority over dynamical time symmetry. As we said, the authors claim from the beginning that their notion of time symmetry is critically different from the standard one. This point is central to their argument, since it is meant to exclude the de Broglie-Bohm pilot wave interpretation and the Everettian theories as counterexamples of time-symmetric theories that do not require retrocausation. As we repeated in different occasions, Price rules them out through PI. Leifer and Pusey (2017) aim to replace it by their time symmetry assumption, so that dBB and Everettian approaches are excluded simply because they violate time symmetry. Moreover, it seems clear that Leifer and Pusey (2017, p. 4) consider their time symmetry as more relevant and fundamental than the standard dynamical time symmetry, as they claim: "we therefore think that it is surprising that a conventional realist (non-retrocausal) interpretation cannot satisfy **Time Symmetry** and that the fact that Everett and dBB do not is a *genuine* deficiency of those theories" (our emphasis). This passage, we consider, shows the strong character of their time symmetry assumption, and the deviation from the standard notion of dynamical time-symmetry. In fact, dBB-Everett must reproduce the prediction-retrodiction symmetry of the formalism, since they are interpretations of quantum mechanics. Is it also recognised that these theories are dynamically time-symmetric in the standard sense: the dynamics of both theories follows the Schrödinger equation, which is left invariant under a time reversal transformation. In dBB, the guidance equation for the particles' position is also dynamically invariant under time-reversal. Nevertheless, these theories are not time-symmetric.[26]

Our conflict, then, is that the authors justify the symmetrisation of the models arguing that they are restoring a fundamental symmetry that in practice is distorted by the thermodynamic arrow of time, but at the same time they do not take as fun-

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[25] For the thermodynamic asymmetry see, for instance, (Price, 1996), (Albert, 2000) and (Uffink, 2001).

[26] For the explanation of why dBB and Everettian-style theories are not ontologically time-symmetric we redirect the reader to (Leifer and Pusey, 2017, p. 18).

damental the dynamical symmetries, which are at the bottom of the explanations regarding the asymmetry of the second law of thermodynamics. The time-directed behaviour of thermodynamics is usually understood as a product of an asymmetrical boundary condition, and the difficulties to explain it arise given the *dynamical* symmetries of classical mechanics. In this debate, the central question is how to explain the asymmetries of thermodynamics given the dynamical symmetries of the underlying theory, statistical mechanics. Thus, it seems difficult to defend that the model must be operationally time-symmetric at the fundamental level if the dynamical time symmetries, which are the reason to hold that operational time symmetry must hold, are not fundamental. In other words, the symmetries of the fundamental laws of physics are dynamical, so, in order to claim that such symmetries should be restored in the operational scenario, it seems compulsory to believe that they are more elementary than the operational symmetries.

The case of (Price, 2012) is different. His argument is that the symmetrisation is done by means the 'Demon on the left', and it is justified by the dynamical symmetry of physical laws: the dynamics of fundamental physical laws is time symmetric, and the thermodynamic behaviour is explained by the asymmetry of boundary conditions (the initial state is not exchangeable with the final state). Thus in Price's case, the introduction of the Demon *is justified* by the dynamical symmetry of physical laws. So, once again, the apparent asymmetry is due to the boundary conditions, but the laws of physics are time-symmetric, and because of that it, it is reasonable to restore the symmetry.

We consider that Leifer and Pusey do not have this justification available. The problem for them is that either (i) they restore the symmetry because they consider that the *fundamental laws* are time-symmetric, in which case, they cannot cut the ice with respect to dBB and Everett, and, even less, claim that the operational time symmetry gives better evidence to infer ontological time symmetry than the dynamical time symmetries of physical laws; or (ii) they just *assume* that the world is time-symmetric (in another sense than the standard dynamical symmetry), and that every asymmetry is emergent. The problem of this last option is that, in this case, the assumption under discussion, i.e., LPIII, is not needed: we would not need to infer the ontological time symmetry from the operational time symmetry. Rather, the operational time symmetry would be *assumed* right from the start, and moreover, it would be the justification for the symmetrisation of the operational setup. If the ontological time symmetry is the logical justification for the symmetrisation, of course, we cannot consider the latter as evidence for the former (it would be both the antecedent and the consequent of the reasoning). In conclusion, we regard that the authors do not provide a clear and justified view of operational time symmetry, and the derived ontological time symmetry could be an artifact of the *ad hoc* symmetrisation (except that they assume the ontological symmetry, in which case this assumption is not well posed).

We see two possible solutions to the problem under discussion: (a) we could add the standard dynamical notion of time symmetry to the assumptions of the retrocausality theorem as a way to restore the validity of LPIII. In this case, we would have three different conceptions of time symmetry in one theorem, and we would need to explain the relation between the operational time symmetry, the ontological time symmetry, and the dynamical time symmetry. Without entering into details, the three notions of time symmetry *might* turn out being not compatible between each other. As (Leifer and Pusey, 2017, p. 18) point out, "the operational and dynamical time symmetry disagree on what is the time reverse of an experiment", since the dynamical time symmetry takes measurements and preparations quantum mechanically, while the operational time symmetry does not. We consider that this alternative requires further investigation, accompanied by a proper account of the three different definitions of time symmetry and what they would imply in the quantum context. We shall leave this for future research.

(b) The second alternative that we envisage consists in taking seriously Leifer and Pusey's suggestion that their LPIII is an attempt to not include discreteness (PI) as an assumption of the theorem. The reason for doing that lies in the generalised character they aim to give to the theorem.[27] As Leifer and Pusey (2017, p. 2) put it:

> Like Bell's theorem, we are aiming for a result that is independent of the details of quantum theory, so that we can say whether or not a given operational theory allows for a time symmetric ontology. In order to do this, we have to replace one of Price's assumptions, which he calls *Discreteness* by a broader principle that can be formulated at this level of generality. Doing so clarifies the precise notion of time symmetry that is at stake in the argument.

Following these lines, it is possible to replace LPIII by the *conjunction* of PI and PIII.[28] This means that, instead of using Leifer and Pusey's non-standard conceptions of time symmetry (and the supposed inferential ground that operational time symmetry gives to ontological time symmetry), we can employ the dynamical notion of time symmetry, at the costs of reintroducing discreteness as an additional assumption. We called this reconstruction of Leifer and Pusey's theorem, the modified retrocausality

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[27] Note that, as the authors explicitly recognise, achieving the mentioned level of generality is the motivation for dispensing of PII as well, which is replaced by LPII: "the first aim of this paper is to construct an alternative to Price's argument, which does not assume the reality of the quantum state. This turns out to be possible using a different assumption that we call **λ-mediation**, which plausibly holds independently of the status of the quantum state" (Leifer and Pusey, 2017, p. 2).

[28] see 3.2.3 for the discussion of how it is possible to derive the required contradiction with quantum mechanics for the theorem to work using {PI + PIII} instead of LPIII

theorem. In 4, we shall proceed with this alternative for two practical reasons. First, alternative (a) requires a more exhaustive analysis about the relation between the three notions of time symmetry. Second, and more importantly, we aim to apply the retrocausality theorem to time-symmetric collapse models, which are explicitly dynamically time-symmetric and, under a mild condition, discrete. For this reason, time-symmetric collapse models fit better with the modified retrocausality theorem rather than with the original one.[29] But first, let us continue the discussion of Leifer and Pusey's *original* retrocausality theorem.

In conclusion, we consider that this time symmetry assumption is not well founded. However, this is not a big problem for the authors, as long as it is possible to reintroduce the dynamical time-symmetry assumption present in Price's argument plus discreteness. The only cost of this is that the retrocausality theorem loses generality. For the specific purposes of this thesis, our criticism to this assumption do not render the theorem less relevant, since, as we are going to see in 4, we shall apply it to time-symmetric collapse models, which satisfy the dynamical time-symmetry assumption, and, under some mild conditions also the discreteness condition.

LPIV: experimenters can decide what they want to measure and, consequently, how they want to set the parameters, i.e., the controllable variables, of the experiment. This means that the x and y variables are not determined either by what we usually call the past nor the future. In the context of Bell's work, these variables are called free variables and their status is discussed in (Bell et al., 1985).

It is interesting to bear in mind that, if there is a strong difference between superdeterminism and approaches in which the present depends on the future as well as on the past, it lies in this assumption. A superdeterministic approach maintains that the settings x and y are correlated with the λs of the theory by means of a common cause lying in their common past light cone.

LPV: all the uncontrollable variables are statistically independent of the controllable variables that lie in their future, given a complete specification of their past. That is to say, every variable of the model that is not an input has to be conditionally independent of every input variable lying in its 'future', conditioning on all the relevant information.

This assumption entails that the probability distributions have to be decomposed as follows:

$$pr(a, b, \lambda|x, y) = pr(b|a, \lambda, x, y)pr(\lambda|a, x)pr(a|x). \tag{19}$$

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[29] We would like to bring the reader's attention again to the fact that this modification does not imply either giving up the theorem, nor reducing it to Price's set up.

No-retrocausality is intrinsically attached in this argument to λ-mediation. As we pointed out in 1, in a fully time-symmetric theory, where there is no reason to distinguish a direction of time as being more objective than the other, if we accept forward λ-mediation, meaning that the correlations are due to physical states evolving forward in time, we need to accept them as existing as evolving backward in time as well. Otherwise, we violate Price's principle of no temporal double standards.

In the scenario proposed by Leifer and Pusey, no-retrocausality plus λ-mediation imply that the probabilities can be decomposed as:

$$pr(a, b, \lambda|x, y) = pr(b, \lambda, y)pr(\lambda|a, x)pr(a|x). \tag{20}$$

As it is evident by now, this assumption is decisive: the authors suggest that, given the incompatibility of LPI-LPV with the predictions of quantum mechanics, this assumption should be rejected. In the literature, no-retrocausality (or its negation), is formulated in a specific way which may not be exempt of other assumptions. For example, as it is going to become more clear in the derivation of temporal factorizability (coming in the next subsection), assuming no-retrocausality is exactly the same, at least in this context, as measurement independence. No-retrocausality and measurement Independence would be different assumptions in a superdeterministic context, but here these theories are ruled out by LPIII. Additionally, the violation of no-retrocausality (at least in the current debates we are analysing) is always understood within an interventionist or manipulationalist approach to causation.[30]

So far we have discussed in detail Leifer and Pusey's assumptions of the retrocausality theorem. In the next subsection, we shall state the conclusions of the theorem as presented by the authors.

3.2.3 Temporal factorizability and quantum mechanics

The aim of Leifer and Pusey (2017) is to provide a generalisation of Price's argument regarding the indispensability of retrocausality under certain assumptions. In this section we reproduce the derivation of temporal factorizability and its incompatibility with the predictions of the quantum algorithm. Regarding our general research question we shall say that quantum mechanics in the block universe, as long as it requires time symmetry, it also needs retrocausation. But, it seems that whilst time symmetry is something that the physics community would embrace, retrocausality is not. Then what?

Let's see how the assumptions LPI-LPV are applied to the preparation-measurement model. This is done through what we called the retrocausality theorem, which first

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[30] For a characterisation of the interventionist approach to causation see (Pearl, 2009), and for the manipilationalist account see (Woodward, 2005).

shows that temporal factorizability is a logical consequence of the assumptions, and subsequently proves that factorizability is at odds with quantum mechanics.

An ontological model, defined as an ontic extension of an experiment satisfying both no-retrocausality and λ-mediation, of an experiment that satisfies free choice and time symmetry, imply a local condition analogue to spacelike factorizability.

The first stage of the retrocausality theorem: an ontological model – which involves no-retrocausality and λ-mediation – of an experiment that satisfies free choice and time symmetry imply a temporal analogue of spacelike factorizability. This temporal factorizability should be conceived as related to temporal locality – in a similar way as spatial factorizability is associated with local causality –. In the words of Leifer and Pusey (2017, p. 13): "let (P, M, T) *be an experiment that has an operational time reverse. If its ontic extension satisfies* ***No-retrocausality,*** ***λ-mediation*** *and* ***Time Symmetry*** *then*

$$pr(a, b, \lambda) = pr(a|x, \lambda)pr(b|y, \lambda)pr(\lambda). \tag{21}$$

" We identify two steps in the derivation. Step (I) involves the derivation of measurement independence and parameter independence from no-retrocausality and time symmetry. Step (II) concludes locality from the introduction of outcome independence plus the results of step (I).

Step (I) In way analogous to the derivation of spacelike factorizability (see 2.2.2), in order to conclude a condition that guarantees temporal locality, measurement independence and parameter independence are required. The following is a reproduction of the **Lemma 8.2** of (Leifer and Pusey, 2017), and its proof.

Given an experiment (P, M, T), with an operational time reverse and with an ontic extension satisfying no-retrocausality and time symmetry, then the probabilities have to decompose as follows:

$$pr(\lambda|x, y) = pr(\lambda) \tag{22}$$

$$pr(b|\lambda, x, y) = pr(b|\lambda, y) \tag{23}$$

$$pr(a|\lambda, x, y) = pr(a|\lambda, x). \tag{24}$$

The first expression (22) is an instance of measurement independence (given time symmetry), and the remaining two represent parameter independence. The proof goes this way (see (Leifer and Pusey, 2017, p. 13): As we have shown, no-retrocausality entails that the probabilities decompose as

$$pr(a, b, \lambda|x, y) = pr(b|\lambda, x, a, y)pr(\lambda|a, x)pr(a|x). \tag{25}$$

By Bayes' theorem, we have that

$$pr(\lambda|a, x) = \frac{pr(a|\lambda, x)pr(\lambda|x)}{pr(a|x)} \tag{26}$$

Replacing this back into equation (25) we get

$$pr(a, b, \lambda|x, y) = pr(b|\lambda, x, a, y)pr(a|\lambda, x)p(\lambda|x). \tag{27}$$

Summing over a and b we get $pr(\lambda|x, y) = pr(\lambda|x)$. Now, time symmetry implies that we can switch the roles of x and y and a and b in (25) to obtain

$$pr(a, b, \lambda|x, y) = pr(a|\lambda, x, y, b)pr(\lambda|b, y)pr(b|y). \tag{28}$$

Applying again Bayes' theorem and summing over a and b gives us $pr(\lambda|x, y) = pr(\lambda|y)$. Tying up the previous results, we have that $pr(\lambda|x, y) = pr(\lambda|x) = pr(\lambda|y)$. Therefore λ cannot depend either on x nor on y: $pr(\lambda|x, y) = pr(\lambda)$. Substituting this result into (27), and summing over b gives

$$pr(a, \lambda|x, y) = pr(a|\lambda, x)pr(\lambda). \tag{29}$$

Dividing by $pr(\lambda|x, y)$ we get

$$pr(a|\lambda, x, y) = pr(a|\lambda, x) \tag{30}$$

As parameter independence requires, and in the time-reversed decomposition, the same argument gives us

$$pr(b|\lambda, x, y) = pr(b|\lambda, y). \tag{31}$$

In words, we consider that the authors are providing the subsequent reasoning:

> (i) By No-retrocausality, λ can only depend on the parameters of past measurements, that is, on input variables on its past.
>
> (ii) But, by time symmetry, it is not possible to identify which parameter, either x or y, is in the past and which is in the future in an absolute way. Thus, we would have a violation of measurement independence by means of retrocausality (at least in one of the temporal directions).
>
> (iii) Points (i) and (ii) are in contradiction, except if we regard λ as independent of both past and future parameters, that is, x and y.
>
> (iv) Thus, $pr(\lambda|x, y) = pr(\lambda)$.

(v) In this model, measurement independence grants parameter independence: whilst the former maintains the independence of λ over the settings x and y, the latter establishes the independence of the measurement outcomes over the settings of the measurement devices from other times. Given λ-mediation, the settings can only have an effect over a measurement outcome performed at other time through an influence to λ so parameter independence collapses into measurement independence.

Let's comment briefly on the role played by LPIII and LPV in this argument. On one hand, we consider that LPV by itself is sufficient to block violations of measurement independence (in this particular context in which superdeterminism is left aside by LPIV.) On the other, LPIII makes λ uncorrelated with both inputs of the model, x and y. Without the later, we would be able to identify either x or y as the parameter in the future. But notice: by the very definition of time symmetry employed by the authors, we cannot infer by the output of the measurement which was the input of the preparation (nor the other way around)! As we explained, this is due to the fact that, given LPIII, the model employs the non-signalling sector of the theories, where (17) and (18) hold.[31] Thus, the step (I) of the derivation concludes that through the assumption of LPIII and LPV, it is inferred measurement independence and timelike parameter independence.

Step (II) In a way analogous to the spacelike case, in order to derive the temporal factorizability condition, outcome independence is needed (in addition to measurement and parameter independence). Now, the outcome independence condition is introduced by assumption, since Leifer and Pusey (2017, p. 14) claim that λ-mediation is the timelike equivalent of outcome independence, implying that

$$pr(b|a, \lambda, x, y) = pr(b|\lambda, x, y). \tag{32}$$

Remember that in the spacelike context, outcome independence is a condition expressing that the statistical correlations between two measurement outcomes performed at spacelike separation should be screened-off by a complete specification of

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[31] This is also the case in Price's argument, where the Demon on the left fulfills this function. However, as we defended, Price's is justified in introducing the symmetrisation since he employs the standard definition of time-symmetry of dynamical laws. We can anticipate that the indispensable use of the non-signalling sector of the theories is one of the reasons why we consider that at the fundamental level time-symmetric quantum theories exhibit temporal global correlations, which do not violate measurement independence (and, given the definition of retrocausality, they do not violate no-retrocausality). Measurement independence *might* be violated only once we introduce agents and the thermodynamic arrow of time, which is exactly what one wants to rule out by the employment of the non-signalling sector of a theory.

λ. In other words, given λ, outcomes at spacelike separation can only be correlated through physical mediation. In the timelike case, we have that two timelike separated events can be physically correlated only through the ontic states, which 'carry' the information or records from one time to another, so that there is *temporal locality*. A full specification of the ontic state between two events must screen-off every statistical dependency between them. The violation of this condition would entail that there are non-local correlations, in this case, between preparation and measurement. As we shall see in short, this non-locality is understood by Adlam (2018b) in terms of *action-at-a- -temporal-distance*. In contradistinction with the last alternative, we shall argue that timelike non-locality, conceived as the negation of λ-mediation, which amounts to timelike outcome dependence, means that there are temporal global correlations between events. This means that there are statistical dependencies between the uncontrollable variables of the theory that cannot be screened-off by intermediary states.

From **step (I**) and **step (II)**, a temporal factorizability follows. Schematically, given realism and free choice, we have that:
Time symmetry + no-retrocausation (meaning measurement independence + parameter independence) + λ-mediation (timelike outcome independence) $\Rightarrow$ temporal factorizability.
Next, the second stage of the retrocausality theorem consists in showing that the temporally local measurement-preparation model is incompatible with the predictions of quantum mechanics. Timelike factorizability "is incompatible with some experiments in the no-signalling sector of quantum theory, for the same sort of reason as it is incompatible with Bell inequality violating experiments in the spacelike case" (Leifer and Pusey, 2017, p. 14). This means that, after the symmetrization of the setup, that is, given a condition that guarantees non-signalling in any time-direction, there are experiments which are not compatible with LPII, LPIII, and LPV. The predictions of the model for the experiment disagree with the predictions of the quantum algorithm, and thus with the experimental results, in the *same* cases as a spacelike Bell inequality is violated. In other words, factorizability holds in timelike case in the same circumstances in which the correlations can be explained by additional variables in the spacelike case (see (Leifer and Pusey, 2017, p. 15)).

With this result at hand, we do not have any other alternative than facing the usual question to which these theorems lead: what premise should we give give up? We shall answer this question from different perspectives, but let's consider first the resolution offered by the authors of the retrocausality theorem. Notice, however, that our project does not finish with pointing out which of the assumption may be violated, but by accounting for such a violation.

LPI, LPII, and LPIV are considered by Leifer and Pusey as indispensable premises for any realist theory. Hence they discard them as options to give up. They also suggest that LPIII should not be rejected, since it displays an important characteristic of fundamental theories. In addition, they appeal to no fine-tuning: both LPIII and LPV are no fine-tuning assumptions. Our ability to signal towards the future, and infer a causal arrow as running forward, should be considered as an emergent feature. This emergence, the argument goes, explains why we need to tune the model. "It is therefore plausible that the possibility of signalling into the past in a universe with retrocausality would be washed out by the same process from which the thermodynamic arrow emerges" (Leifer and Pusey, 2017, p. 23). Thus, given that the thermodynamic arrow of time associated with the possibility of signalling is emergent, giving up LPV seems the most natural option.

Moreover, from Price's principle of no temporal double standards it follows that, if λ-mediation together with time symmetry are maintained, then what is needed is an argument to justify no-retrocausality. Once we accept that there is a state evolving forwards in time, there has to be another state evolving backwards, unless we provide a good reason to maintain that there are properties that apply only in one temporal orientation. Thus, given LPIII, if LPII is admitted as involving forward causality, then we should swallow the whole ontological package, retrocausality included. Once again, this is not only because no-retrocausality would be the only alternative left to give up, but also because we shall avoid temporal double standards.

But, why hold on to their own assumption of time symmetry, LPIII? As we argued, we consider that this assumption, as it stands in the paper, is not well founded. Nevertheless, as we said, this can be fixed by appealing to dynamical time symmetries and introducing discreteness. This is what Price (2012), Price and Wharton (2017), Evans et al. (2013) do. In fact, this is the alternative we shall follow in 4, where we apply the retrocausality theorem to time-symmetric collapse models. Thus, although we shall not give up time symmetry, since our specific research question aims to study the consequences of time-symmetric quantum mechanics, we are not forced to hold on to LPIII. We shall take the alternative strategy which considers the standard notion of dynamical time symmetry (as it appears in PIII). It is important to highlight again that this move is legitimate, since as Leifer and Pusey (2017, p. 15-6) admit, it is possible to derive the incompatibility of the preparation-measurement model with quantum mechanics as well by replacing LPIII by the conjunction of PI and PIII:

> Price summarizes his argument as *Realism* + *Time symmetry* + *Discreteness* ⇒ *Retrocausality.* To give a similar form to our result, this can be rewritten as
>
> **No Retrocausality** + *Realism* + *Time symmetry* + *Discreteness* ⇒ Contradiction (with quantum theory)."

Notice, that PII, is replaced in Leifer and Pusey's retrocausality theorem by LPII, since they do not want to leave outside of its the scope theories that are not realist about the quantum state.

Modified retrocausality theorem: the modified retrocausality theorem has six assumptions:

LPI Single world realism

LPII λ-mediation

PI Discreteness

PIII Time symmetry

LPIV Free choice

LPV No-retrocausality

Mutatis mutandis, the structure of the argument and the conclusions do not change with the modified retrocausality theorem: we have to reject one of the assumptions, and, given the aims of this thesis, we are not considering the rejection of PIII. We shall not consider the option of giving up PI either, since the results would not be so interesting. The natural consequence of the arguments previous arguments in this section is still giving up LPV.

In the next section, we show that there is another alternative to give up, namely LPII. As we anticipated, this is explicitly proposed by (Adlam, 2018b), following previous work by Wharton (2015). We concur with Adlam, and in 4, we shall show that TSCM proposed by (Bedingham and Maroney, 2017a) provide a good example of this. Nevertheless, Adlam's rejection of LPII (λ-mediation) is conceived as implying action-at-a-temporal-distance, and a restoration of determinism. We do not believe that this is the best way to interpret the results. In opposition, we consider that the rejection of this assumption should be seen as involving temporal global correlations between measurement outcomes across histories. We argue that temporal global correlations do not imply action-at-a-temporal-distance, in a similar way as violations of outcome independence in the spacelike scenario do not imply action-at-a-distance, but only non-locality (see 2.3).

3.3 Action-at-a-temporal-distance

In the previous section we saw that Leifer and Pusey's retrocausality theorem claims that a model meeting LPI-LPV implies a timelike factorizability condition that has similar consequences to spacelike factorizability, namely, it generates predictions that are inconsistent with OQM. We also saw that the modification of the theorem, that replaces LPIII with {PI + PIII} gives the same results. So, in any case, the consequence is that we are compelled to give up one of the assumptions. Leifer and Pusey claim that the most natural option to give up is LPV and embrace retrocausality. In this section, we shall explore the alternative offered by Adlam (2018b), which consists in rejecting that every correlation is mediated by an ontic state, that is, that λ-mediation (LPII) does not hold. It is important to notice that, even if this offers an alternative to avoid giving up the idea that there is no retrocausality in the quantum domain Leifer and Pusey's retrocausality theorem, Price's setup, and consequently, the modified retrocausality theorem, teach us a significant moral that should not be underestimated: time-symmetric quantum theories require non-trivial correlations between future and past events.

The core of the argument proposed by Adlam (2018b) is that the notion of temporal locality is deeply involved in most of the puzzling results of QM, and it has never been put into doubts. Because of this, we are facing the risk of turning this feature into a dogma. Regarding the specific topic of our research, we saw that Leifer and Pusey's LPII guarantees temporal locality. Conversely, giving up this assumption implies temporal non-locality. This temporal non-locality, Adlam claims, implies action-at-a-temporal-distance.

Temporal locality is defined by Adlam (2018b, p. 2) as follows:[32]

> Suppose that two observers, Alice and Bob, perform measurements on a shared physical system. At some point t_a, Alice performs a measurement with setting a and at some time $t_a+\delta$ she obtains a measurement outcome A; likewise, at some time t_b, Bob performs a measurement with measurement setting b and at some time $t_b+\delta$ he obtains a measurement outcome B. Let $\lambda(t_a)$ be the state of the world at time t_a and let $\lambda(t_b)$ be the state of the world at time t_b. Then:

$$pr(A,B|a,b,\lambda(t_a),\lambda(t_b)) = pr(A|a,\lambda(t_a))pr(B|b,\lambda(t_b)), \tag{33}$$

or, as we prefer:

$$pr_{a,b}(A,B|\lambda(t_a),\lambda(t_b)) = pr_a(A|\lambda(t_a))pr_b(B|\lambda(t_b)). \tag{34}$$

The satisfaction of this condition means that every temporal correlation between two experiments is mediated by the state of the world at the time in which the measurement is performed; every correlation is mediated by an ontic state. In other words, the condition implies that "there is a physical state that carries information from one time to another by means of its dynamical evolution" (Adlam, 2018b, p. 4).

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[32] In (33), we write $pr(B|b,\lambda(t_b))$ instead of $pr(A|b,\lambda(t_b))$, which has a typo.

Adlam (2018b) sketches three approaches in which this condition could be violated, namely, by means of: (i) non-Markovian laws (ii) non-local retrocausality, and (iii) atemporal, 'all-at-once' laws. We must confess that we do not see a clear characterisation of the differences between these three alternatives.[33] In fact, non-local retrocausality seems to entail non-Markovian laws, which are also part of the 'all-at-once' approach. In honour of brevity, we shall mention only the 'all-at-once' view, since this seems to be the author's preferred alternative, as it is also discussed in(Adlam, 2018a) and (Adlam, 2021).[34]

The key of the 'all-at-once' approach is that the dynamics of the systems emerges *en bloc* from initial and final boundary conditions. In her own worlds (Adlam, 2018b, p. 2):

> . . . our theory may fail to be temporally local by being atemporal, meaning that the course of history is determined 'all-at-once' by external, global laws of nature, in much the same way as the rules of the game of sudoku apply to the whole grid at once rather than dictating the entries column by column from left to right. In such a theory, the result of a measurement at a given time may depend on global facts even if there is no record of those facts in the state of the world immediately prior to the measurement, and thus an atemporal theory will usually be temporally nonlocal unless of course the theory tells us that the state of the world at time t always contains complete information about the history of the entire universe.

We can appreciate the close relation with λ-mediation: 'all-at-once' theories would be non-local since there would not be an ontic state mediating every timelike correlation.

Our aim here is not to give a full and deep characterization of the 'all-at-once' approaches, but just analysing the alternative they propose for the interpretation of the retrocausality theorem. This consists in exploring the characteristics that a theory that denies λ-mediation would have. In consequence, we shall point out two characteristics of Adlam's approach that we challenge in the next section.

First, 'all-at-once' approaches imply 'spooky-action-at-a-temporal-distance'. The negation of this feature is what temporal locality guarantees: "...in a temporally local world there would be no action-at-a-temporal-distance, i.e., all influences on a measurement outcome would be mediated by the state of the world immediately prior to the measurement" (Adlam, 2018b, p. 2). Interestingly, Price (2012, p. 79) directly addresses this question:

> The symmetry argument does not go through if we deny that the usual quantum polarization τ_L is a beable, or element of reality... τ_L would

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[33] This is not meant to be a criticism since we believe that Adlam is proposing a conceptual framework for future developments.

[34] Notice that Adlam considers that the 'all-at-once' views are retrocausal.

> normally thought to be what 'carries' the signal, or causal influence, from one side of the apparatus to the other. Denying that there is any beable to play this role seems to amount to accepting a kind of action-at-a-distance (although timelike, rather than spacelike).

And then, he adds in a footnote of the quoted passage that in (Evans et al., 2013), they argue that temporal non-locality ought to be regarded as analogous to spatial non-locality.[35] This alternative, which is the point that Adlam (2018b) is making, is rejected by Price (2012) since, instead of solving the puzzle of spacelike non-locality, it would add even more action-at-a-distance to the quantum realm than what was expected.

We are convinced that, although locality implies *no* action-at-a-distance, the converse is not true. That is to say, a temporally non-local theory does not have to involve the spooks Adlam (and Price) refers to. Bearing in mind the analogy between the spacelike and the timelike cases, we shall recognise that spacelike non-locality *per se* is not taken to imply spacelike action-at-a-distance. This is exactly what we discussed in 2.3. In stochastic models of a Bell experiment, non-locality can be understood in terms of global correlations.

Second, as it is the case in general with the locally-retrocausal approaches, Adlam's goal is to recover determinism and determinateness. "The universe could be *deterministic* in a generalized sense when the global variables are taken into account, whilst appearing probabilistic to agents as ourselves who do not have access to the whole picture" (Adlam, 2018b, p. 40). The strategy now is being realist about external global laws that rule the behaviour of entities. By external global laws, what is meant is that there are atemporal laws of nature, laws lying 'outside' time that govern the entire history of the universe (or phenomena between boundary conditions) (Adlam, 2021, p. 20). We find this view about laws difficult to understand, and hardly scientifically motivated. So, leaving aside the issue of what these external global laws might be, the idea is that the probabilities in quantum mechanics would arise only given our temporal perspective on the block universe. We consider that the negation of temporal locality can perfectly be understood in an indeterministic setup.

3.4 Time-symmetric quantum might exhibit temporal global correlations

In the previous sections, we discussed Price and Leifer and Pusey's arguments claiming that, under certain circumstances, time-symmetric quantum mechanics requires retrocausality. More specifically, we first saw that in (Price, 2012) setup it is shown

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[35] Notice that in the previous quote, if we have in mind the retrocausality theorem, Price could be referring to a rejection of either LPI or LPII.

that a time-symmetric quantum theory that is realist about the quantum state and that only allows discrete outcomes requires retrocausality. Then, we discussed the generalization offered by Leifer and Pusey (2017), which consists in a theorem that proves that any quantum theory meeting a set of assumptions entail a temporal factorizability condition, which leads to predictions that conflict with quantum mechanics. To account for this, Leifer and Pusey claim that we should choose between rejecting their own assumption of time symmetry or embrace retrocausality. They suggest to give up no-retrocausality, which necessarily implies violations of measurement independence. In this context we advanced a modification of the retrocausality theorem, which, following an alternative mentioned by Leifer and Pusey, consists in replacing their controversial assumption of time symmetry by the conjunction of dynamical time symmetry plus discreteness. The result does not vary: following the arguments of Price and Leifer and Pusey we need to reject either dynamical time symmetry or no-retrocausality (as we shall not even consider the option of giving up discreteness). Next, we reviewed the proposal of Adlam (2018b), which consists in giving up a third assumption, namely, λ-mediation. The rejection of this latter condition would involve temporal non-locality, and thus, according to the author, action-at-a-temporal-distance. In this section, we take seriously the temporally non-local direction that Adlam proposes, although we provide a new interpretation of what it does entail. Taking distance from the 'all-at-once' approach and its action-at-a-temporal-distance, we shall show that there is another alternative, namely, that time-symmetric quantum mechanics exhibits mere temporal global correlations. These temporal global correlations are fundamental, and they cannot be screened-off. Thus, we have three different views about what time-symmetric quantum mechanics in the block universe requires: retrocausality, action-at-a-temporal-distance, and temporal global correlations.

In the literature about the physical significance of Bell's theorem there are different proposals about what *spacelike* non-locality means. In 2.3, we discussed two alternatives: on one side, non-locality is supposed to imply action-at-a-(spatial)-distance and, on the other, non-locality is interpreted as indicating global correlations between events at spacelike separation. The former appears in the EPR-argument, and in Bell's early deterministic models. Then, in the indeterministic models, action-at-a-distance arises as a violation of parameter independence. In contradistinction, the global correlations are associated with indeterministic theories in which there are no causal dependencies between settings and outcomes at spacelike separation, but between outcomes and outcomes.

Thus, global correlations have a different status than action-at-a-distance: (i) they cannot be used to signal, or in the words of Shimony (1984), they amount to an uncontrollable non-locality, (ii) and hence they do not involve an asymmetric temporal order between events, which is also guaranteed by the commutative character of the measurement operators at spacelike separation. As a consequence, (iii) unlike action-at-a-distance, the global correlations, also characterised as ‘passion-at-a-distance’, do not involve causation, since the latter are asymmetric relations. In conclusion, global correlations are implied by violations of outcome independence, and although they involve non-locality, they do not imply action-at-a-distance. We are convinced that this reasoning sheds light on whether the *temporal* non-locality involved by the rejection of λ-mediation involves action-at-a-temporal-distance, or temporal global correlations.

Price’s setup, Leifer and Pusey’s retrocausality theorem and its modification, and Adlam’s ‘all-at-once’ approach, are based on the assumption that timelike and spacelike correlations are analogous.[36] This assumption can be challenged, as for instance Rijken (2019). But, given that our subject matter here is precisely analysing the consequences of the retrocausal arguments, we take for granted that the analogy holds. *Contra principia negantem non est disputandum.* Thus, we argue that given Leifer and Pusey’s characterization of λ-mediation as a temporal analogue of outcome independence, its violation can be interpreted in a similar way to the spacelike case, namely, as implying temporal global correlations. Despite that these temporal global correlations involve non-locality, they do not imply action-at-a-temporal-distance. Our argument requires a theoretical distinction between the role of parameters and outcomes, congruent with Seevinck and Uffink (2011, p. 8) suggestion:

> ...[parameters and outcomes] have very different roles in any putative candidate theory we envisage, and this means that we should not regard them on equal footing, at least theoretically. Although their ontological (or physical) status might be the same, their theoretical status is not. And this is crucial. Especially since local causality refers to putative candidate theories only. Thus, the difference between the two must be adequately reflected in any candidate theory

Although both, settings and outcomes are expected to be beables, in our context, the settings of measurement devices are *asymmetric* temporally local variables (closely attached to the thermodynamic arrow of time), whereas measurement outcomes are temporally non-local. This means that, unlike the event of arranging the settings of an apparatus, performing a measurement and getting a result, measurement outcomes depend on the entire history of outcomes, in a way that they do not satisfy the Markov condition.

In a dynamically time symmetric quantum theory compatible with the block universe perspective, measurement outcomes at timelike separation can be non-trivially

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[36] In both Leifer and Pusey, and Adlam’s arguments this is explicit. Given what we discusses so far, the reader may be more hesitant about whether this is also the case in Price’s approach. It is. Even if it is not explicitly said in the specific papers we have considered so far, it is a central part of the Price’s view. This can be verified in (Evans et al., 2013).

correlated. If λ-mediation is not met, a measurement outcome at t', does not depend only on the state of the system at the previous moment, t, but also on its entire history. That is to say, if the theory is time-symmetric in a way in which the laws are blind to a time orientation, then every measurement outcome depends on both its past and future history.

The relation between measurement outcomes cannot conceptualised in causal terms. Given time symmetry, the nomological description of the history of outcomes is left invariant whether we consider the forwards or backwards in time dynamics. The consequence of this is essential for our argument: in a temporally non local theory, there is nothing in the laws that enables the ascription of causal dependencies to the set of measurement outcomes. Remember, causality is an asymmetric relation, which is time-oriented (even if it does not need to be attached to a 'master' time's arrow). Causes are not swapped with the effects in a time-reversal transformation. In a dynamically time symmetric theory, measurement outcomes clearly do not show this asymmetry. Taking, for instance, the initial and final states, there is no absolute way to tell which one is the cause and which one is the effect. Both of them could be causes *and* effects, which is incompatible with the notion of causation we are employing in this research. The moral, then, is that the dependencies of measurement outcomes along the temporal axis are temporal global correlations arising at the statistical level; they cannot be used to signal; they are not causal; and they do not display 'spooky-action-at-a-temporal-distance'.

The relation between *settings* and *outcomes* is different. The settings are controllable variables that may have an effect on the outcome, and this in an asymmetric way. Once we ascribe to the event of fixing the knob settings of an apparatus the role of being a causal factor of a measurement outcome, the relation cannot be inverted. As we also saw in the retrocausal arguments, a time-reversal transformation does not switch inputs and outputs. This is a point made explicit by Leifer and Pusey, and underlies Price's setup as well. Therefore, according to this conceptualization, the correlations between the settings and the outcomes at a given time are causal.

Bearing this in mind, a central point of our argument is the following: if a time-symmetric quantum theory show signs of non-local dependencies between the *settings* and the *outcomes*, then the model exhibits action-at-a-temporal-distance, just as Adlam maintains (see 3.3. Similar to the spacelike case, this would be due to the possibility of sending 'instantaneous' signals to other moments in time. Here, the concept of 'instantaneous' signalling across the temporal dimension sounds by itself mysterious. The idea, though, is intelligible: if time flows at a given rate (at an emergent level), there would be signals that could be sent faster than that rate, i.e. taking a shorted time lapse. Metaphorically, in these cases it would be possible for a scientist to send a message towards himself five years older without the need to wait five years. The message is 'instantaneous' and non-local since it is not transmitted by an ontic state evolving on time, but rather by means of causal dependencies between settings and outcomes that are not mediated by the state of the world at intermediary times. That is to say, these correlations would not leave records in the intermediary states. In conclusion, temporally non-local correlations between *settings* and *outcomes* would imply the possibility of signalling 'instantaneously', and thus affecting outcomes, along the entire history of events. As Rijken (2019, p. 61) shows, this seems to be the case in 'all-at-once' theories, where every variable is correlated with every other variable.

> . . . the values of all parameters (both boundary and intermediate parameters) become statistically dependent on each other. You cannot change the value of one parameter without that change affecting the entire space-time region in question. The resulting picture of the world is that of a static block universe where all parameters are interconnected, and where the dynamical asymmetric-in-time description thereof is merely an approximation.

Taking this analysis into consideration, we shall conclude that if there are non-local correlations between *settings* and *outcomes*, then there is not just a violation of λ-mediation (LPII), but of no-retrocausality (LPV) as well. This is due to the fact that there would be outcomes (non-controllable variables) that depend on *settings* (controllable variables) lying in their future. If all the parameters (which in this context are understood as physical variables) depend on each other, then every outcome depend on every setting (including the settings lying on their future).

Now, it is important to consider that, given time symmetry, the presence of correlations between settings and outcomes would imply the possibility of signalling both from past to future and from future to past. We claim that we should take seriously the fact that an essential part of Price's setup, Leifer and Pusey's retrocausality theorem, and consequently our modification of the retrocausality theorem, lies in the impossibility to signal from experiments or measurements performed at timelike separation. As we saw, without this, none of the time symmetry assumptions hold, and hence there is no need for retrocausality. This is the reason why the dynamical notion of time symmetry employed by Price required the introduction of the 'Demon on the left', and Leifer and Pusey's time symmetry was restricted to the non-signalling sector of the theories. The consequence of this is that we should not be able to infer from a measurement outcome which components of a system were measured at other times. In other words, the probabilities for an outcome at a given time are independent of the settings of the measurement devices at other times.

As a conclusion, we wish to point out that our approach is in line with Maroney (2017) argument that operationally disturbing measurements are incompatible with the use of pre- and post-selection. This means that if we consider that there are dependencies between settings and measurements at timelike separation, which are not screened-off by the measurement outcomes at intermediary times, then performing a measurement must change the probabilities of outcomes at other times. This since we would be able to infer from the outcomes at, let's say t, if a measurement was performed and the values that where measured at t', or t'', where $t' < t < t''$.

In what follows of this thesis, we shall introduce time-symmetric collapse models and show that they should be interpreted as exhibiting temporal global correlations, and not retrocausality or action-at-a-temporal-distance. This will expand our characterization of temporal global correlations by means of an analysis about how these models violate Leifer and Pusey's λ-mediation assumption.

The moral for our general research question is that if the block universe perspective requires time-symmetric quantum mechanics, then it provides a reconciliation with special relativity only if time-symmetric quantum mechanics requires retrocausality or action-at-a-temporal-distance. As we saw, both retrocausality and action-at-a-distance (at least in Adlam's 'all-at-once' approaches) entail a violation of the measurement independence condition. Such a violation enables a local explanation of the deviation of quantum mechanics from Bell inequalities. If time-symmetric quantum mechanics involves temporal global correlations, measurement independence is not violated, so in this case, the block universe perspective would not provide a new point of view regarding the spacelike case of Bell's theorem.

4 Time-symmetric collapse models: a study case

In the previous sections, we saw that time-symmetric quantum mechanics can be interpreted as involving retrocausality, action-at-a-temporal-distance or temporal global correlations. In this section, we show that there is an explicit example in favour of the interpretation of temporal global correlations, which consists in time-symmetric collapse models, proposed by Bedingham and Maroney (2017a).

The first subsection is devoted to an introduction to the measurement problem in quantum mechanics, which leads us to a presentation of dynamical collapse models in the second section. Then, in the third subsection, we discuss why the standard interpretation of dynamical collapse models is temporally asymmetric. There is, however, an alternative, which is introduced in the fourth section, based on a flash ontology and the introduction of time-symmetric boundary conditions. This alternative results in an example, discussed in the fifth section, of how time-symmetric quantum mechanics can be interpreted as exhibiting temporal global correlations.

4.1 Preliminaries: the measurement problem in quantum mechanics

What is considered a good solution to the measurement problem, and an assessment of the magnitude of the further puzzles introduced by a solution to it depends on our philosophical position. To express this, we can borrow Rovelli's slogan: any solution to the measurement problem involves giving up a belief about how the world is, that seems so natural and justified in our classical experience (see, for instance, (Rovelli, 2021)). In this section, we aim to explore one narrative of possible solutions to this problem that leads us to the dynamical wave-function collapse theories, and then to 'collapse theories as beable theories' (borrowing from (Bacciagaluppi, 2010)). Given our specific purposes, we do not aim for a complete nor fully objective presentation of this issue.[37]

Collapse theories are attempts to solve the quantum measurement problem by a modification of the Schrödinger equation. In this sense, these theories do not constitute an interpretation of quantum mechanics, but, they provide new physics (as Maudlin (1995) says). The key feature is that the wave function does not evolve always unitarily, but it is rather subjected to random jumps from time to time, depending on the number of systems with which it interacts. The greater the number of (or size of) interacting systems, the greater the probability that collapses take place, leading to the suppression of interference and superposition. Before delving into dynamical collapse theories, let us explain the measurement problem using unitary quantum mechanics.

Consider a system in superposition of, let's say, being spin-up and spin-down in the z-direction, and let it evolve unitarily according to the Schrödinger equation. Next, let the particle interact with a measurement apparatus set to perform a z-direction measurement of the particle. By the same dynamics, the pointer of the apparatus should evolve to a superposition of the two possible measurement outcomes: 'up' and 'down'. And then, this superposition can be 'pushed inside the head': if the dynamics is *always* linear and unitary, this state should lead to a superposition of what a scientist sees on the screen of the measurement apparatus. Moreover, the

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[37] Maudlin (1995) offers a very powerful formulation of the measurement problem, which does justice to the mainstream theories and interpretations of quantum mechanics, based on the recognition that the following three claims are mutually inconsistent: (A) The wave function of a system is complete. (B) The wave function always evolves in accord with a linear and unitary dynamical law. (C) Measurements have single (non-relative) and determinate outcomes in accord with our classical experience. The heuristic strength of this formulation is that it enables us to appreciate how the different interpretations and quantum theories solve the problem, that is, which of the claims they reject. De Broglie-Bohm pilot-wave theory rejects (A). Standard formulations of Dynamical collapse theories reject (at least) (B). Everett's interpretation, Relational Quantum Mechanic, and the Many-Worlds interpretation reject (C).

scientist would have to be in a superposition of believing that the particle is 'up' and 'down'. Butterfield calls this "von Neumann's chain" ((Halvorson and Butterfield, 2021, p. 6)), meaning that following the Schrödinger equation, we should add terms to the superposition, so that at some point there would be scientists having "indefinite, or superposed, experiences". This superposition is a legitimate state of the world according to quantum mechanics which cannot be interpreted as our lack of knowledge about the actual state of the system.

Nevertheless, our experience is not in accordance with this narrative. We rather always observe the apparatus' dial pointing either to 'up' or 'down', and, through self-inspection, we always realise that we have definite mental states about what we see. The story is not different regarding other properties or degrees of freedom. As the famous double-slit experiment shows, a system can be in a superposition of two positions, but once we perform a measurement, or we observe by which slit the system is going, it always has a definite position. We experience physical objects as being 'here' or 'there', and never as $1/\sqrt{2}(here–there)$. Once again, the last expression should not be interpreted to mean that the system is 'here' or 'there', and that we do not know where it actually is. If the wave function represents the real and complete state of the system, how do we explain this fact? This is the measurement problem concerning definite outcomes

Aiming to account for this quantum weirdness, Von Neumann proposed that there are two types of processes in quantum mechanics:

> (A) Unitary evolution: the system follows the Schrödinger equation, and thus its evolution is deterministic, unitary and linear.
>
> (B) Projection postulate: when a measurement is performed, the system does not follow any more the Schrödinger equation, but a discontinuous collapse of the wave function onto an eigenstate of the observable that is being measured. Thus, the linearity is somehow broken, and, at the end of a measurement process we always recover a single determinate outcome. This means that if the system was evolving guided by a deterministic, unitary and linear law in a superposition of all the possible measurement outcomes, once the measurement is performed the state of the system changes to an eigenstate of the measured observable.

From a realist point of view, this approach is unsatisfactory since it opens up a more general class of problems, also identified under the scope of the measurement problem. Granting that von Neumann's introduction of two different dynamical rules for the wave function goes in the right direction, two different problems follow. Given that quantum mechanics aims to be a comprehensive theory that applies to every physical system, we need to know, on one hand, at which level of description the dynamics of the system is no longer given by (A), and an effective or physical collapse of the function takes place. That is is to say, *where* does the transition from (A) to (B) take place? Another way to problematise this is by demanding an unambiguous demarcation of the domain in which classical concepts do not longer apply. As Bacciagaluppi and Valentini (2009, p. 141) put it: "where does macroscopic definiteness give away to microscopic indefiniteness? Does the transition occur somewhere between pollen grains and macromolecules, and if so, where? On which side of the line is a virus?" In a nutshell, a satisfactory interpretation of quantum theory, when it address the measurement problem, it is supposed to deal with the vagueness of the quantum-classical, micro-macro, distinction.

On the other hand, we may stick to the idea that there is no real need for demarcation; measurements always have outcomes and quantum mechanics is a theory to make probabilistic predictions about them. It does not matter *where* exactly the ontological or effective cut between the classical and the quantum lies. Performing a measurement corresponds to the projection of the state onto an eigenstate of the observable with a probability equivalent to the mod-squared of the eigenvalue. The strong deficiency of this alternative is that we should be able to describe the measurement process itself quantum mechanically, since the measuring device is – at the appropriate microscopic scale in which classical concepts do not apply – a quantum system as well. Otherwise, we may start asking: what special system is a measuring device that triggers the process (B) under interaction with the wave function? What is the distinction between a measuring device and a quantum system? How is it possible that these apparatuses have a preferred dynamical role in a theory that is supposed to explain the behaviour of all systems at a given scale? The measurement problem in this respect is that we cannot attribute a preferred dynamical role – collapsing the wave function or projecting a state in superposition – to measurement processes without a proper explanation. In other words, we cannot take measurements just as primitive concepts that do not need explanation, as the following famous rhetorical passage by Bell (1989, p. 216) suggests:

> What exactly qualifies some physical systems to play the role of 'measurer'? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little bit longer, for some better qualified system... with a Ph.D.? If the theory is to apply to anything but highly idealised laboratory operations, are we not obliged to admit that more or less 'measurement-like' processes are going on more or less all the time, more or less everywhere? Do we not have jumping then all the time?

A solution to the measurement problem, in this sense, should include either an explanation of why measurements have a preferred dynamical role or provide a theory in which they do not have such a role. Given that measurements, in the strict sense of the word, are human actions, and that observing should count as a measurement, this has been called the issue of quantum mechanics without observers (see, for instance, (Bacciagaluppi and Valentini, 2009)).

It is important to notice that these variants of the measurement problem are framed within a realist perspective. There are interpretations of quantum mechanics that regard it to be incomplete, and consider it to refer only to ensembles. A form of the measurement problem also applies to these theories, since they require an account of when it is possible to talk about individual systems and when this talk is precluded. This would be a variant of the conceptual vagueness of quantum mechanics to discriminate between what is micro and what is macro (see (Bacciagaluppi and Valentini, 2009)).

These puzzles, among others, have been at the core of the philosophy of quantum mechanics in one way or another since its formulation. Up to date, there is no common agreement, and this has led to different quantum theories or interpretations. The three mainstream interpretations in the philosophy of physics community are: (i) de Broglie-Bohm pilot-wave theory (see (Goldstein, 2021) and references therein), (ii) the Everett interpretation and the Many-Worlds interpretation (see (Wallace, 2012) and (Saunders, 2021)), and (iii) the dynamical collapse theories. In the next section, we shall focus on the last kind of theories. De Broglie-Bohm and Everettian-Many-Worlds interpretations are beyond the scope of this thesis mostly because they are not discrete theories, so that they violate PI which is one of the assumptions of the modified retrocausality theorem. Regarding our general hypothesis, although this theories are time-symmetric in the standard dynamical sense, they still implement asymmetric boundary conditions, which generate time-oriented phenomena. Without the introduction of a wave function evolving backwards, the asymmetry cannot be explained as conventional or associated with the thermodynamic arrow of time, so that they fit better within the 'B-series' of time rather than the 'C-series'.

4.2 Physical collapse solves the measurement problem

In the last section, we saw that the measurement problem is a set of open questions, as for instance: why measurements have a definite outcome? At which level of reality does the classical realm end? Where and when are the classical concepts no longer applicable? How can we account for quantum mechanics without observers, or what triggers a measurement process? Dynamical collapse theories are attempts to answer these questions that became popular in the mid-80s. There are various dynamical collapse theories. The most famous, and first one developed, is quantum mechanics with spontaneous localization, also called GRW model in honour of its creators, Ghirardi, Rimini, and Weber. This theory is followed by the continuous spontaneous localization model (see (Pearle, 1989) and (Ghirardi et al., 1990)). In the second part of this thesis, we will focus only on the first proposal. There are two reasons for this decision: first, GRW are the models that have been mainly studied in the time-symmetric setting, and second, in such cases, the models are interpreted in terms of a flash ontology, which is problematic in the continuous case. The essential feature of all collapse theories is that they modify the Schrödinger equation, turning it nonlinear and stochastic. Thus, these theories propose a single and unified dynamics that accounts for both the quantum domain and the macroscopic definite realm with which we interact. The collapse of the wave function is regarded as a physical process that takes place randomly, without attributing any special dynamical role to measurements.

Collapse theories are guided by two basic principles:

> (1) Macroscopic objects, such as measurement apparatuses and tables, ought to have well defined relative localization. Usually, the preferred basis, that is the basis in which the reduction takes place, is position (as it is the case, for instance, in GRW models).
>
> (2) The dynamics of the theory ought to preserve the quantum properties ascribed by OQM to the micro-world, at the same time that it meets (1). This means that it needs to allow interference and superposition at the micro-level, and suppress it at the macro-level (of course, without making fundamental reference to measurements). The criteria that this condition seeks is an amplification process from micro to macro.

Considering that the ability of collapse theories to save the phenomena depends on (1) and (2), it is important to add some comments. *Prima facie* these two principles might not seem reconcilable, but they have been unified in one dynamical law. To achieve this, it is required the introduction of two new constants of nature: the localization accuracy, and the mean localization frequency. The first constant of nature determines the rate of spontaneous localization, or collapse, for a single particle, while the second defines a length scale to which the widely spaced wave function collapses during the localization process (see, for instance, (Bassi et al., 2013) and (Ghirardi and Bassi, 2020)). These two parameters are crucial to solve the measurement problem in its different variants, since they allow, for example, to define the 'split' between micro and macro, and they explain why macroscopic objects in superposition would collapse in less than a second.

There is discussion in the literature about what the precise values of these parameters are.[38] This is very important since they ought to lead to a theory that meets the predictions of OQM and our phenomenological picture of the world. Thus, on

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[38] For some proposals of the values that these parameters take, and the experimental constraints see (Ghirardi and Bassi, 2020) and references therein.

one hand, the spontaneous localization has to take place with higher probabilities at those places where the quantum formalism tells us there are higher probabilities of detecting a particle. If this condition is not met, then our new physical picture would considerably differ from the predictions of OQM, which have shown high empirical success. On the other hand, particles have to be subjected to spontaneous localization in a way such that the localization occurs with a frequency relative to the number of particles of a system (or a similar quantity as, for instance, mass-density.) The more particles the system has, the faster it has to be localised. In other words, the model cannot go without showing that when a considerable number of particles interact, they end up being very well localized in spacetime. The relevance of this last point lies in the need to explain why tables and coffee mugs are not in a superposition of being 'here' and 'there', at least, in our everyday experience.

In order to analyse how these theories stand regarding the main goal of this thesis, that is, whether they are compatible with the block universe perspective, as standardly defined, and, consequently, whether they require retrocausation or not, we will need to specify more the dynamics of the theory. Bearing in mind the goals of this thesis, we shall ask whether collapse theories are compatible with the block universe perspective, or not. Then, if they are, we should ask whether they require retrocausality, action-at-a-temporal-distance, or temporal global correlations. The last question should shed light on whether collapse theories in the block universe are reconcilable with special relativity or not. We shall follow the account given by Bedingham and Maroney (2017a).

As we highlighted, the physical insight in which collapse theories are grounded is the idea that collapses are not just triggered by observations but happen more or less all the time. This is presented as follows. Let's take the wave function $\psi_t(x_1, x_2, ..., x_N)$ for N distinguishable particles, which evolves most of the time following the Schrödinger equation. The theory postulates that this evolution is broken by random and spontaneous collapses, which occur with fixed probability per unit time for each particle. Simply put, the wave function is not all the time evolving according to a unitary and linear dynamics, but it is subjected to collapses every once in a while. The rate and probabilities for such a collapse are given by the already mentioned parameters. Thus, when we observe or measure physical systems, we see definite outcomes *because* the wave function suffers spontaneous jumps from time to time. Given the size of a measurement apparatus, entangling it with a system to perform a measurement just increases the probabilities of a jump. The jump of the wave function is represented as

$$\psi_{t+} = j_i(z)\psi_t, \tag{35}$$

where j is the collapse operator acting randomly on each particle i at different random times. In the right hand of the equation, we see the action of the collapse operator on the wave function just prior to collapse, and in the left hand we see the wave function at the time after the collapse. The definition of the collapse operator is

$$j_i(z) = \frac{1}{(\pi a^2)^{\frac{1}{4}}} e^{-\frac{1}{2}\left(\frac{z-x_i}{a}\right)^2} \tag{36}$$

with the label j from 'jump', following (Bedingham and Maroney, 2017a). Here, a is one of the relevant parameters introduced by the theory that fixes the relevant length scale.

Recall that in these quantum theories the preferred basis is position. It will turn out to be very important to notice that z represents the collapse centre to which the wave function for particle i is quasi-projected by the action of the collapse operator. Taking this into account, we shall recognise that, what we observe in spacetime is actually the variable z. As we shall see in 4.3, this variable can be interpreted in different ways. In the wave-collapse picture, it represents where the wave function is highly localised. We never see the uncollapsed wave function, which lives in a $3N$-dimensional configuration space (where N is the number of particles of the wave function), in order to see it, it needs to interact with macroscopic objects.[39] These interactions lead to a very fast collapse. Thus, we only observe the collapsed wave function since macroscopic objects do not last in superposition longer than a split of a second. If we take collapse events as the primitive objects of the theory, then z is the point in spacetime where collapse occurs.

The recovery of the statistical predictions of OQM is guaranteed by the Born rule. In fact, the collapse of the wave function with centre in z takes place following the Born rule for a quasi-projection of the form:

$$\frac{\int dx_1...dx_N |j(z-x_i)\psi_t|^2}{\int dx_1...dx_n |\psi_t|^2} \tag{37}$$

So far, we have reviewed the general structure of dynamical collapse theories and the dynamics they propose for the wave function. Let us give more details about the GRW models.[40]

In collapse models in general, and in GRW models in particular, the unitary evolution of the quantum state is interrupted by random spontaneous jumps. When there is no jump taking place, we represent the unitary evolution from time s to t of the quantum state, with Hamiltonian $H = H^*$ as

$$|\psi_t >= U(t-s)|\psi_t >, \tag{38}$$

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[39] For the ontology of the wave function see, for instance, (Albert, 1992), (Lewis, 2004) and (Chen, 2017).

[40] Notice that the CSL model can be recovered as a limit case of the GRW.

where $U(t) = e^{-iHt}$.

Suppose now that at t there is a jump. In accordance with what we said previously – but using now Dirac's notation – the effect of such a hit is given by the application of the jump operator, $J = J^*$, to the quantum state at t:

$$|\psi_t> \rightarrow |\psi_{t+}> = J(z_t)|\psi_t> \tag{39}$$

Naturally, the jump operators have to satisfy the completeness property

$$\int dz J^2(z) = 1. \tag{40}$$

Finally, given the quantum state ψ_t, the probability of the jump having the specific outcome z at time t is given by

$$P(z) = \frac{< \psi_t|J^2(z)|\psi_t >}{< \psi_t|\psi_t >} \tag{41}$$

At this point the relation between collapses and measurement outcomes become evident: collapses have the form of spontaneous fuzzy measurements of position with outcome z. The measurement outcomes are the collapse events, and thus, a measurement outcome is nothing different as the variable z. In the words of Bedingham and Maroney (2017a, p. 674), "the jump operators are generalised quantum measurement operators. The effect of the jumps on the quantum state is therefore equivalent to the effect of performing the corresponding measurement."

To conclude this section, we shall highlight the similarities of collapse theories with OQM. As we saw, the former has the benefit over the latter of solving the measurement problem by the construction of a stochastic non-linear dynamics that unifies the two processes identified by von Neumann. But, as Bell (1987, p. 205) recognises, this is done in a very similar way to OQM:

> In all this the GRW account is very close to that of a common way of presenting conventional quantum mechanics, with 'measurement' causing 'wavefunction collapse' – and with a 'measurement' somewhere causing 'collapse' everywhere. But it is important that in the GRW theory everything, including 'measurement' goes to the mathematical equations of the theory. Those equations are not disregarded from time to time on the basic of supplementary, imprecise, verbal, prescriptions.

Thus, there is a common structure between the two theories. The similarities extend to what would be the natural ontological interpretation of the theories. In what follows, we will name *standard collapse theories*, those interpretations of collapse theories that consider the wave function or the quantum state as the fundamental ontology, and regard it as a complete and accurate description of individual quantum systems. Like *realist* interpretations of OQM, standard collapse theories do not require additional variables or many-worlds to provide a complete description of a system; what we macroscopically observe is the localized quantum state. As Bacciagaluppi (2010, p. 5) puts it:

> In this sense, the theory is about the wave function. The wave function is what there is, the ontology of the theory, or at least, the visible manifest part of the ontology, while the hits [i.e., the jumps or collapses] are part of what determines the evolution of the wave function.

Using Bell's concepts, we shall say that the beables of the theory are constituted by the wave function or the quantum state. However, leaving aside that the wave function does not even live in spacetime, it is difficult to regard it as a local beable since the measurement outcomes associated with its localisation display correlations at a distance in a Bell-type scenario. With Myrvold (2016), and Shimony (1984), we shall be aware of the fact that these theories are usually interpreted as been spatially non-local, in the sense that they exhibit global correlations at spacelike separation or, as Shimony puts it, 'passion-at-a-distance'. This kind of non-locality must be differentiated from the action-at-a-distance encompassed in other quantum theories, as for instance, the de Broglie-Bohm pilot wave theory, which is based on a violation of parameter independence.

4.3 Wave function collapse as a time-asymmetric process

In the first part of this thesis, after introducing the issue of spacelike non-locality, we critically presented the retrocausality argument by Price (2012), the retrocausality theorem by Leifer and Pusey (2017), and our modified retrocausality theorem. The latter consist in a change of LPIII by the conjunction of PI and PIII. We also saw that it is possible to challenge some of their assumptions and, at the same time, recognise some important morals of the arguments. For example, Adlam (2018b) challenged LPII, λ-mediation, and maintained that theories that violate this condition imply action-at-a-temporal-distance. By our side, we showed that time-symmetric quantum mechanics without λ-mediation may be interpreted as exhibiting temporal global correlations – which are different from retrocausality and action-at-a-temporal-distance. Now, we are in a position to analyse if these approaches apply to, and give us new insights about, collapse theories. To address this question, it is necessary to bring in some distinctions between the wave-collapse ontology and the collapse-as-beable pictures. The standard collapse models we reviewed in the previous section take the wave function as the fundamental building block of the theory. However, there are other alternatives: it is possible to consider that the fundamental objects of these models are constituted by a $3D$-ontology.

How should collapse theories be understood in light of the modified retrocausality theorem? Can collapse theories live in the block universe? The quick intuitive answer is that these theories would not require either retrocausality, action-at-a-temporal-distance or temporal global correlation because they exhibit a fundamental time asymmetry. Given that the crucial feature that a theory needs to meet to be compatible with both the modified retrocausality theorem and the block universe perspective is dynamical time symmetry, collapse theories seem to be out of scope. As an example, we can appreciate that the temporal asymmetry provides a good argument to introduce a fundamental arrow of causation oriented in one time-direction, without violating the principle of no temporal double standards proposed by Price (1996). After all, there is no better argument for giving *priority* to a temporal direction than a temporal asymmetry. Let's delve briefly into this.

As we have seen in section 4.2, the collapse of the wave function is a physical interpretation of the projection postulate to solve the measurement problem. Concerning this point, Bacciagaluppi et al. (2008, p. 706) point out that "while at first sight the Schrödinger equation may seem time-symmetric, the projection postulate is definitely time-asymmetric, so that to the list of puzzles that measurement brings into quantum mechanics one needs to add that of time-asymmetry." In GRW the projection postulate is englobed in a unified dynamics that enables modelling the measurement processes, although in a way that introduces an arrow of time that is not usually considered as part of our fundamental theories (and this is the reason why "one needs to add [the issue of] time-asymmetry").

Similarly, in the summary about the puzzles of quantum mechanics, Price (1996, p. 229) states the following: "the problem of time asymmetry[:] as standardly represented, collapse is time asymmetric – it depends on the past but not the future, in a way which does not seem explicable either as harmless conventional asymmetry or as of the same origins as the thermodynamic asymmetry."

Even in a stronger phrasing, López (2018, p. 2,n.3) comments that both the projection postulate, and the jumps in the GRW, give rise to a genuine arrow of time:

> On the one hand, most physicists are quite familiarized with the 'Postulate of Collapse of the Wave Function.' … this kind of evolution does give us a genuine time-asymmetric process one could base a direction of time on. On the other hand, a more general formulation of Collapse of the Wave Function (independent of measurements) is that presented by Ghirardi-Rimini-Weber (GRW) interpretation of quantum mechanics. According to this interpretation, not only do quantum systems evolve conforming to the

> Schrödinger's time-dependent equation but also to a continuous stochastic evolution that makes the quantum system 'jump' to a definite value each a certain amount of time. This evolution also gives us a fundamental direction of time since quantum systems experiment these 'hits' in only one temporal direction.

Thus, if we consider the metaphysical debate between presentism and eternalism (that is, the block universe perspective), the *standard* opinion is that the physical collapse of the wave function favours presentism (or variants as the growing block universe), since it involves an intrinsic time-directedness.

Callender (2017, p. 94-6) also analyses the supposed quantum becoming implied by a real collapse mechanism, and points out that the standard interpretation is that the wave function is collapsed in the past, while in the future it is in a superposition between different eigenstates of a given observable. This would show a fundamental qualitative difference between past and future. This can be illustrated in a very intuitive way: if we think retrospectively in Einstein's single slit thought experiment, we can appreciate that, let's say at t, the wave function was spread out over space, whilst at t'', after a collapse took place at t', it is pretty well localised. The jumps are a radical ontological change that renders past and future qualitatively different.

We need to point out another element of the standard interpretation of collapse models as time-asymmetric. The probabilities for a collapse event having a definite value are usually understood as constrained by the collapse events relative to the past. Borrowing from (Bedingham and Maroney, 2017b, p. 1) "according to the orthodox view of quantum theory, an observation leads to a collapse of the wave function in accordance with the observed result. This updating procedure results in a state that is shaped by past measurement events but not future ones. A physical wave-function collapse process therefore suggests an arrow of time in the fundamental dynamical laws." Thus, even if we take the dynamics of collapse theories without being realists about the collapse *mechanism* (and we take it rather as an inference or updating) there would still be time asymmetry. The reason is that, the very notion of state seems to be time-directed, as long as we use it to make predictions about the future, based on the information of the past.

All these features are exhibited, for instance, in the characterisation made by Shimony (1986) of quantum mechanics in terms of potentialities, which are also known as propensities. Propensities are metaphysical properties that are stochastic in nature and can behave in different ways depending on their environment or interactions. The key feature is that they behave in different, indeterministic, ways which can be probabilistically quantified. For instance, a photon may have the propensity to collapse 'here' or 'there' (and the Born's rule tells us how to weight the probabilities of each possibility). In the words of Shimony (1986, p. 142):

> The combination of indefiniteness of value with definite probabilities of possible outcomes can be compactly referred as *potentiality*, a term suggested by Heisenberg (1958, p. 1985). When a physical variable which initially is merely potential acquires a definite value, it can be said to be *actualized*.

For Shimony, dynamical collapse theories provide a non-anthropocentric account of how the actualisation process is triggered. The ontology of propensities and the stochastic dynamics that describes their tendencies is, again, *not* time-reversal invariant. In (Shimony, 1990, p. 65), for instance, he comments an auxiliary virtue of the collapse approaches:

> The implications of a modified dynamics, however, may reach far beyond the original motivation. In particular, a stochastic modification of quantum mechanics can hardly avoid introducing time-asymmetry. Consequently, it offers an explanation at the level of fundamental processes for the general phenomenon of irreversibility, instead of attempting to derive irreversibility from some aspect of complexity (which has the danger of confusing epistemological and ontological issues).

The actualization of the potentiality would imply a fundamental arrow of time, the arrow of collapse, and this is seen as a virtue of collapse theories.[41]

Finally, we shall also mention Bell, and venture to speculate that a possible reason for this view may be the (misleading) belief that stochastic theories are *per se* time-asymmetric since probabilities imply that the future is open while the past is fixed (see, for example, (Arntzenius, 1995)). In this context, Bell (1984, p. 177) claims that:

> The stochastic transition probabilities [dtT_{nm}, which represents the transition probabilities from a jump from n to m in the interval dt] replace here the deterministic guiding equation of the de Broglie-Bohm 'pilot wave' theory. The introduction of a stochastic element, for beables with discrete spectra, is unwelcome, for the reversibility of the Schrödinger equation strongly suggests that quantum mechanics is not fundamentally stochastic in nature.

The conflict that Bell is indicating seems to be between the time symmetry implied by the deterministic equation and the corresponding asymmetry that stochasticity introduces. The idea is that indeterminism implies that the future is open whilst the

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[41] More recent characterisations of quantum mechanics in terms of propensities have been advanced by Suárez (2007).

past is fixed. However, as we mentioned in 1, the issue regarding whether the world is deterministic or indeterministic is different from the question about time symmetries and the block universe perspective (see also Bacciagaluppi (2020)).

Now, the specific question regarding whether the indeterminism of collapse introduces a strict distinction between past and future, and a consequent asymmetry, has been lucidly addressed in (Callender, 2017, p. 95). Given its clarity, we would like to quote the passage completely:

> Does quantum mechanics, on a collapse interpretation, support one's pre-theoretical views of the openness or mutability of the future(...)? It's not so clear. We can approach the question by asking whether the open/fixed distinction maps neatly into the superposition/eigenstate distinction. The answer is 'no'. To begin, the symmetry of Hilbert space implies that we can write out our wavefunction in any of an indefinite number of bases, e.g., position, momentum, spin. A wavefunction that is a superposition in one basis may not be a superposition in another; for instance, the wavefunction of x-spin down in superposition of up and down spins in the z-spin direction. Here a collapse to fixity in x-spin buys openness in z-spin.

We could present a longer parade of quotes and positions, but let's just take the moral: the general consensus, with a few exceptions like Callender, seems to be that the collapse postulate in OQM and the physical collapse mechanism in dynamical reduction models, including GRW models with wave-ontology, violate time symmetry. We consider intriguing that the debates on quantum mechanics have not given enough relevance to time symmetries. This has not been the case with other physical theories that at first sight seem time-asymmetric as well. This is the reason why we concur with Price's project that time symmetry could be an important clue to disentangle some mysteries of the quantum realm.

In the remaining of this thesis we shall delve into a recent proposal by Bedingham and Maroney (2017a), that renders GRW models time-symmetric. In the next section, we shall account for how this time symmetry is achieved and present the proof offered by the authors. Subsequently, we come back to the question that opened this section, namely, how should collapse theories be understood in light of the modified retrocausality theorem? The answer to this question will lead us to our conclusion.

4.4 Time symmetric collapse models and the collapse as beables' ontology

In this section, we have introduced the measurement problem and how collapse theories solve it. We saw that, *in general*, the collapse of the wave function is seen as time-asymmetric. We shall see that the time-asymmetry is relative to what we called the standard interpretation of collapse models. There are interpretations of the ontology of collapse theories that are not based on the wave function, as for example, the flash ontology. This view maintains that the fundamental objects of the theory are the collapse outcomes. Then, Bedingham and Maroney (2017a) show that, if we take the flash ontology, it is possible to build time-symmetric collapse models. In what follows, we shall present this proposal. We called it time-symmetric collapse models (TSCM). After, we scrutinize whether they require retrocausality, 'spooky-action-at-temporal-distance', or temporal global correlations. We will show that these models support our proposal that time-symmetric quantum mechanics might exhibit temporal global correlations.

In his essay 'Are there Quantum Jumps', Bell (1987, p. 205) suggested that we could consider a $3D$-ontology for GRW models:

> ...the GRW jumps (which are part of the wavefunction, not something else) are well localized in ordinary space. Indeed each is centred on a particular spacetime point $(\mathbf{x}, t)$. So we can propose these events as the basis of the 'local beables' of the theory. These are mathematical counterparts in the theory to real events at definite places and times in the real world (as distinct from the many purely mathematical constructions that occur in the working out of physical theories, as distinct from things which may be real but not localized, and as distinct from the 'observables' of other formulations of quantum mechanics, for which we have no use here).

This idea was then developed in terms of the so-called flash ontology, which considered the collapse events (or 'hits') as the fundamental objects of the theory. These flashes were not compatible with continuous spontaneous localization models. So, following a similar spirit, a localised mass-density ontology, determined by the wave function, was proposed. The intuitive reason is that both the flashes and the mass-densities are well localised in our $3D$-space, being thus a quite natural ontology to explain our phenomenal experience (see (Allori et al., 2008), (Bacciagaluppi, 2010) and references therein). In what follows we shall focus on the flash ontology, since, as we stated, we are taking into consideration GRW models.

It may be important to highlight that this flash ontology gets rid, as a first straightforward step towards peaceful coexistence, of the instantaneous collapse of the wave function, opening a door for the construction of a Lorentz invariant collapse theory. We consider that, although the previously quoted statement by Bell is open to different understandings regarding the status of the wave function, it sets the tone for a nomological interpretation of it.

Having this in mind, Bedingham and Maroney (2017a) show that if we take seriously the physical picture in which the fundamental objects are the collapses, that is a flash ontology, and we set suitable boundary conditions, then we have dynamical collapse models that are time-reversal invariant. The time-directed picture, and the Born rule, which prescribes probabilities for future outcomes based on information we gathered in the past, are recovered as a special case with asymmetric initial and final conditions.

Thus, an important element to have time symmetry in quantum mechanics is the introduction of symmetric boundary conditions.[42] In this case, these are given by a final mixed state ρ_F and, consequently, an initial mixed state ρ_I. These density matrix states stand for our uncertainty about which is the realised pure state, providing us with a probability distribution over them. If we take the initial state and we let it evolve, it will give us a history of collapses. The physics is time-reversal invariant since if we take the final state and we evolve it backwards in time, it will give us the same history of collapse events. Moreover, given that the joint probability distribution is the same in each time direction, we do not have any means to tell whether the set of collapses is described by the forward or the backward dynamics.

More technically, fixing both an initial state, ρ_I at t_0, and a final constraint on the universe, ρ_F at t_n, we take the collapses to occur at discrete times t_i between t_0 and t_n. Employing the standard collapse dynamics (38) and (39), the unnormalized state at a time t with $t_j < t < t_{j+1}$ is given by

$$\rho_t = U(t - t_j)J(z_j)...U_{2,1}J(z_1)U_{1,0}\rho_I U_{0,1}J(z_1)U_{1,2}...J(z_j)U(t_j - t), \tag{42}$$

where $U_{i,j} = U(t_i - t_j)$ and $z_i = z_{t_i}$ (see (Bedingham and Maroney, 2017a)).

Remember that equation (41) gives us the probabilities for a specific jump at t given the quantum state at that time. Thus, with that formula, we can determine the probability for the complete set of collapse outcomes for the entire history of the universe. The authors of the model show that the history of the whole set of events, conditional on initial and final states is given by

$$P(\{z_i\}|\rho_I, \rho_F) = \frac{P(\{z_i\}, \rho_F|\rho_I)}{P(\rho_F|\rho_I)} = \frac{Tr[\rho_F \rho_n]}{\int dz_1...dz_{n-1} Tr[\rho_F \rho_n]}, \tag{43}$$

with $\rho_n = \rho_{t_n}$.

Then, Bedingham and Maroney proceed to define the condition under which (43) has a time symmetric structure by means of the existence of a basis in which both U and J, that is the unitary and the jump operators, are symmetric matrices. Formally, the condition stipulates that there has to exist a complete set of basis states $\{|\phi_i>\}$

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[42] The introduction of symmetric boundary conditions, and the corresponding experimental pre- and post-selections, have been introduced as means to articulate time-symmetric interpretations of quantum mechanics by Aharonov et al. (1964) and Aharonov and Vaidman (1998).

such that

$$\begin{aligned}< \phi_i|U(t)|\phi_j >^* &= < \phi_i|U(-t)|\phi_j >; \\ < \phi_i|J(z)|\phi_j >^* &= < \phi_i|J(z)|\phi_j > .\end{aligned} \tag{44}$$

In order to show thatTSCM meet this condition, it is needed first to define a ρ^*:

$$< \phi_i|\rho^*|\phi_j > = < \phi_i|\rho|\phi_j >^*, \tag{45}$$

from that definition, the authors derive the time-reversed of (43)

$$P(\{z_i\}|\rho_I, \rho_F) = \frac{Tr[\rho_n^* \rho_F^*]}{\int dz_1 ... dz_{n-1} Tr[\rho_n^* \rho_F^*]} \tag{46}$$

Then, what is needed is a notation for the collapse events in the reverse ordering: the new time parameter is $\bar{t} = -t$, and consequently $\bar{t}_i = -t_{n-i}$ such that $\bar{t}_0 < \bar{t}_1 < \bar{t}_2 ... < \bar{t}_n$. Then, $\bar{z}_i = z_{i-n}$ and $\bar{U}_{i,j} = U(\bar{t}_i - \bar{t}_j)$ so that

$$\rho_n^* = \bar{U}_{0,1} J(\bar{z}_1) ... \bar{U}_{n-2,n-1} J(\bar{z}_{n-1}) \bar{U}_{n-1,n} \rho_I^* \bar{U}_{n,n-1} J(\bar{z}_{n-1}) \bar{U}_{n-1,n-2} ... J(\bar{z}_1) \bar{U}_{1,0} \tag{47}$$

Inserting this into (46), we get

$$P(\{z_i\}|\rho_I, \rho_F) = \frac{Tr[\rho_I^* \bar{\rho}_n]}{\int d\bar{z}_1 ... d\bar{z}_{n-1} Tr[\rho_I^* \bar{\rho}_n]}, \tag{48}$$

where it is used the cyclic property of the trace and

$$\bar{\rho}_n = \bar{U}_{n,n-1} J(\bar{z}_{n-1}) \bar{U}_{n-1,n-2} ... J(\bar{z}_1) \bar{U}_{1,0} \rho_F^* \bar{U}_{0,1} J(\bar{z}_1) ... \bar{U}_{n-2,n-1} J(\bar{z}_{n-1}) \bar{U}_{n-1,n}. \tag{49}$$

Now, if we compare equation (43) with (48), we can appreciate that the probability formula could be interpreted as resulting from the reversed set of collapse outcomes $\{\bar{z}_1, ..., \bar{z}_{n-1}\}$, $\{\bar{t}_1, ..., \bar{t}_{n-1}\}$, with initial and final states ρ_F^* at $\bar{t}_0$, and ρ_I^* at $\bar{t}_n$, correspondingly.

In conclusion, we have a backward in time dynamics with an identical form as the forward in time dynamics, with a unitary dynamics between $\bar{s}$ and $\bar{t} > \bar{s}$,

$$|\bar{\psi}_{\bar{t}} > = U(\bar{t} - \bar{s})|\bar{\psi}_{\bar{t}} >, \tag{50}$$

where there is no collapse, and a collapse event at $\bar{t}$ of the form

$$|\bar{\psi}_{\bar{t}} > \rightarrow |\bar{\psi}_{\bar{t}+} > = J(\bar{z}_{\bar{t}})|\bar{\psi}_{\bar{t}} > \tag{51}$$

Thus, in this section we showed, following Bedingham and Maroney (2017a), that GRW models with a flash ontology and symmetric boundary conditions are dynamically time-symmetric. This means that the dynamical laws of the model do not enable a distinction between a forward and backward in time dynamics. As a consequence, there is no reason for positing a preferred direction of time in this theory. Thus, TSCM can live in the block universe, and the retrocausal arguments, specifically the modified retrocausality theorem, can be applied to them. In the next section, we shall evaluate whether TSCM show retrocausality, action-at-a-temporal-distance, or temporal global correlations. As anticipated, we will find that these models exhibit temporal global correlations.

4.5 Do TSCM exhibit retrocausality, action-at-a-temporal-distance, or temporal global correlations?

By the introduction of specific boundary conditions and a proper ontology, collapse models can be interpreted as time-reversal invariant. These models display features that are of utmost interest regarding our broad research question since they are indeterministic theories that are time-symmetric, and thus they are compatible with the block universe perspective. We are entitled now to ask whether these models require retrocausality, action-at-a-temporal-distance, or temporal global correlations.

4.5.1 TSCM in Price's toy-model

Let's consider first Price's scenario, in which the assumptions are

PIDiscreteness.

PII Realism.

PIII Time symmetry.

An essential condition for Price's toy-model is the symmetrisation between the two wings, which must forbid the possibility of signalling only in one temporal direction. Such a possibility may be either due to asymmetric boundary conditions or the presence of epistemic agents with asymmetric access to information. Both of these conditions have to be ruled out in order to quarantine time-directed phenomena.

TSCM might allow signalling if the initial and final states happen to be asymmetric.[43] This would be the case if, for instance, the initial condition happens to be a

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[43] Note that we are leaving out a description of epistemic agents in TSCM. This is due to our current lack of ability to include them in the analysis. However, this should not be directly problematic since adding such agents would never facilitate the study of time-symmetry, but rather the contrary. Since we are focusing on the characteristics of the symmetries rather than the asymmetries, adding them would just complicate things. In any case, it is important to bear in mind that *if* agents were included, *they would not be able to signal given the boundary conditions we shall set.* An additional motivation is our willing to leave aside any possibility of introducing anthropocentrism to the models.

pure state and the final condition a *mixed state.* Nevertheless, Price's argument – and our modification of Leifer and Pusey's retrocausality theorem – ask us to limit our analysis to the non-signalling sector. This can be done by imposing the *maximally mixed state* as the initial and final conditions. If we take as an example a single photon, a maximally mixed state is one that ascribes probability 1/2 to every polarisation outcome. This condition, that forbids signalling, also renders TSCM discrete: the initial state cannot be in superposition. This is because the maximally mixed state can be written as a mixture of eigenstates for *every* observable. In standard dynamical collapse models, the final state is never in superposition (given the collapse mechanism), but there is no constrain on the initial state. Thus, the restriction to the maximally mixed state rules out the option of an initial state in superposition. So, in order to be able to apply the Price's argument – as well as the modified retrocausality theorem – arguments to TSCM, we need to chose the maximally mixed state as the initial and – by symmetry – the final conditions, which grants both PI and the non-signalling condition required by PIII.

Nevertheless, in TSCM the quantum state is not something real in the sense of being an independent entity, existing out there in the world. For this reason, they do not meet PII. In fact, following the lines of Dowker and Herbauts (2005), Bedingham and Maroney (2017a) are open to explore the possibilities of an elimination of the quantum state.[44] In this context, we may consider that Price's argument is dodged in a rather trivial way. Remember that in the argument τ_L is a beable, in this case should be the quantum state, that mediates the L-wing with the R-wing (see 1). Given that in TSCM there is no quantum state that can play such a mediating role, there is not a τ_L correlated with the polarization σ_L, that carries this information towards the R-wing. Consequently, in a dynamically time-symmetric scenario, where we shall not be able to distinguish a preferred direction of time, there is no need for a mediating quantum state to be correlated also with the polarization angle of the R-wing, σ_R, in a way that requires retrocausal effects. In conclusion, if there is not a mediating state τ_L, then there is no need to introduce a retrocausal mediating state τ_R in order to meet the time-symmetry condition.

If someone would want to recover Price's PII in TSCM by positing a quantum state evolving from the L-wing towards the R-wing, the strategy will *not* be straightforward. This is because, a collapse theory that is realist about the quantum state would imply a violation of the time symmetry condition PIII, since the standard notion of state is conceived as encoding its past, but not its future (see 4.3). Furthermore, if we really believe that nature is fundamentally time-symmetric in the sense we are using in this thesis, then we cannot posit only one quantum state evolving in

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[44] The reasoning is that if we consider more and more flashes between the boundary conditions, then the quantum states that dictate the initial and final conditions become irrelevant.

one direction.[45] Such a move would violate Price's principle of no temporal double standards. Therefore, to not violate this principle, we need to posit *two* quantum states, one evolving forward and another evolving backwards. Such a picture would make a collapse model time-symmetric, but, notice, by the introduction of retrocausality since the backwards state would be correlated with the polarization angle σ_R, which is its preparation cube. In this case, Price's argument about the indispensability of retrocausality for time-symmetric quantum theory is no longer useful since we would be introducing retrocausality by stipulation just to make the theory time-symmetric.[46]

In a nutshell, we can interpret TSCM as violating the realist assumption of Price's setup PII but if someone wants to take TSCM forward and reconstruct them as realists about the quantum state, then we need to posit two quantum states, and the argument for retrocausality loses significance. In the next section, we shall apply our reconstruction of Leifer and Pusey's retrocausality theorem, and drawing our conclusions about the characteristics of TSCM.

4.5.2 The implications of the modified retrocausality theorem for TSCM

Let's remind the reader that Leifer and Pusey generalise Price's argument in the form of a theorem. As they declare, one of their main motivations is indeed making a theorem as much independent of the especific characteristics of a quantum theory as possible. For this reason, they aim to dispense of PI and PII, which rule out theories that are not ψ-ontic or discrete. Here we shall just recap the assumptions of the theorem, for a discussion see 3.2.2.

Let's remind the reader that Leifer and Pusey propose a theorem, which we called the retrocausality theorem, that generalises Price's argument. In 3.2.2, we discussed the assumptions, and we criticised their time symmetry assumption LPIII. Then, in 3.2.3, we showed that the retrocausality theorem can be modified in such a way that it LPIII is replaced by the conjunction of PI and PIII. We called this variant of Leifer

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[45] An exception would be conceiving it as correlated with both wings of the experiment (i.e., with the initial and final boundary conditions). Presumably, this would have to entail a sort of retrocausality as well. In any case, it should be noticed that Price addresses this alternative explicitly, see (Price, 2012, p.79).

[46] Notice that the difference with the original argument is subtle: in Price's argument the indispensability of retrocausality is inferred from the the characteristics of the setup. As Leifer and Pusey put it, if a theory meeting Price's premises is not retrocausal, then it is incompatible with the predictions of quantum mechanics. Positing retrocausality to restore an assumption of the model, i.e., time symmetry, is another thing, since there is no incompatibility that needs to be saved. An example could be a realist interpretation of the two-vector states formalism: the backward evolving state would be introduced to have time symmetry). See (Aharonov and Vaidman, 1998), and (Robertson, 2017) a discussion.

and Pusey's theorem, the modified retrocausal theorem.[47]

LPI Single world realism.

LPII λ-mediation.

PI Discreteness.

PIII Time symmetry.

LPIV Free choice

LPV No-retrocausality.

There is a remark worth to be highlighted again: dispensing of LPIII, and using instead PI and PIII *does not* imply that we are analysing the implications of TSCM in lights of Price's toy-model, and leaving aside the retrocausality theorem. Leifer and Pusey build a theorem that consists in showing that some assumptions are incompatible with quantum mechanics whereas Price describes a specific circumstance that requires a retrocausal explanation. Thus, taking seriously a suggestion made by Leifer and Pusey, we claim that we can still have the a modification of the retrocausality theorem if we replace LPIII for {PI + PIII} (see 3.2.3).

The theorem establishes that a theory meeting all these premises should obey a temporal analogue of the Bell's inequalities, which are violated by quantum mechanics. Consequently, we need to give up one of the assumptions. Staying as close as possible to Leifer and Pusey's original argument, we should decide between giving up either time symmetry PIII or LPV, since all the other assumptions, expect PI, are essential for a realistic model. Remember that we shall not consider the option of giving up PI since this would not lead to any interesting result. Moreover, the same condition that makes TSCM non-signalling – a necessary condition to maintain PIII – imposes discreteness (see 4.5.2). Thus, if we do not allow the existence of retrocausality, the violation of the timelike Bell inequalities should be taken as the impossibility of time-symmetric quantum mechanics. Analogously, if we believe that our fundamental theories are time-symmetric (and we take that as an epistemic value or guide), then the result of the temporal variant of Bell's theorem implies retrocausality. It is for this reason that we are entitled to say that, given the assumptions,

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[47] We need to point out important qualification: even if it were the case that we agreed with the *original* retrocausality theorem, we would not have been able to apply the *original* retrocausality theorem. This because, we are not sure about how LPIII could be applied to TSCM. More specifically, we lack the conceptual tools to examine how TSCM would react to the operational and the ontological time symmetry in laboratory conditions. In order to do so, it is needed to give a precise and developed account of *experiments* and how TSCM would work in those scenarios.

if someone believes that any theory that violates measurement independence – i.e., the No-retrocausality assumption LPV – is conspiratorial, then they think that the conjunction of time-symmetry and the other assumptions implies conspiracies.

Which of the assumptions do TSCM violate, if any? Naturally, given that the models respect the predictions of quantum mechanics, and violate Bell inequalities, a proper interpretation of them ought to give up at least one of the premises.

We maintain that TSCM respect single world realism LPI. In fact, we believe that it is a key feature of collapse models in general that they detach from both full-blown anti-realist interpretations and many-worlds interpretations. It may be relevant to highlight that positing a λ, that is, an ontic state, should not be confused with considering that every physical correlation must be mediated by it. Single world realism LPI asserts that there are ontic states, that is, that there are physical properties that take some determined values, which are represented by the theory in question. Notice, again, that the theory is not realist about the quantum state. It rather asserts that the quantum state is part of the dynamical laws, which are conceived as epistemic tools that we use to quantify expectations and make predictions. As such, in principle it is possible to construct other laws that dispense of the quantum state. But, of course, being anti-realist about the quantum state or the wave function does not mean that the theory does not represent physical states at all. In TSCM, collapse events are the stuff out there in the world, and they reveal physical values. Thus, TSCM meet this assumption, being the ontic states the flashes.

Let's continue with the dynamical time symmetry assumption PIII. As we saw in 4.4, Bedingham and Maroney (2017a) show that if we consider the flashes as the fundamental objects of the theory, and we set appropriate boundary conditions, then the theory is dynamically time-symmetric in the standard sense dynamical sense (see 1). If we introduce also the quantum state as part of the ontology of the theory, then the dynamics of the theory is no longer time-symmetric. This is because the state generated by the forward in time dynamics will not coincide with the state generated by the backward state dynamics. "The wave function is time asymmetric for the simple reason that it is defined in a time asymmetric way" (Bedingham, 2018, p. 84).

Thus, if we consider first ρ_I as the initial state and we evolve it towards ρ_F, the final state, following the laws of GRW, we will have the history of collapses described by the forward in time dynamics. In a time-reversal transformation we take the complex conjugate of the final state as the initial state of a new history, that is $\rho_F \to \rho_I^*$, and we evolve it towards the complex conjugate of the initial state of the original history, that is $\rho_I \to \rho_F^*$. Bedingham and Maroney prove that such a time-reversal transformation would leave invariant the *set of collapses*, and the joint probability distributions. In the words of Bedingham (2018, p. 84):

> So, at the level of collapse outcomes $\{z_i\}$ there is time symmetry. The

> stochastic laws determining the probability of a given complete set of collapse outcomes can be used in either time direction, and in both cases they give the same probability. From a dynamical point of view it doesn't matter which is direction of time we use. They both give the same result. Assuming that the collapse outcomes alone (without the wave function) give an empirically adequate description of the world then we can conclude that collapse models are time symmetric.

Now, non-signalling *and* discreteness (PI) are met if we impose the maximally mixed state as the initial and final boundary conditions. In this case, we will find that both the set of collapses and the transition probabilities generated by the forward in time dynamics will be exactly the same as the set of collapses and the transition probabilities produced by the backwards in time dynamics. This specific case, then, entails that TSCM meet {PI + PIII}. Thus, we can conclude that TSCM are dynamically time-symmetric, meeting also the non-signalling and the discreteness condition on specific circumstances, that is, when we consider the maximally mixed state as the boundary conditions.

Before continuing, it might be important to remark that we shall assume that LPIV is satisfied. This assumption should not be problematic as Leifer and Pusey's own characterisation does not go beyond claiming that the parameters are considered as 'free external' variables of the theory.[48]

So far so good. Our discussion showed that if we take the initial condition, ρ_I, and the final condition ρ_F, as the maximally mixed states, then TSCM meet LPI, and the conjunction of {PI + PIII}. We also assumed that LPIV is met. Therefore, if these models are going to satisfy LPV, the only option left is rejecting λ-mediation: LPII. And, in fact, TSCM explicitly violate LPII, enabling us, at least logically, to keep LPV.

As long as TSCM dispense of the quantum state, LPII is violated. The reason is that if we do not consider the quantum state to make predictions about the future, conditioning over information about the entire history of events in the past give us better predictions than considering only events in the immediate past. This conditionalization over the entire history up to the event we are interested in making predictions about, would give us the same results we would get if we use the quantum state. For this reason, the quantum state is so useful and usually considered as indispensable. Regarding this point, Bedingham and Maroney (2017a, p. 672) say:

> The collapsing evolution of the wave function corresponds to an updating, conditioned on the history of realised collapses, of the rule for determining

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[48] Note that a better characterization of this condition would require us to introduce an explicit distinction between inputs and outputs in TSCM, which we are not able to do at the moment.

> the probability of future collapses. The evolving wave function is then just a convenient calculation tool for making the theory Markovian. Going further it can be speculated that the wave function might be abandoned altogether.

Let us unpack what this means. If we have a physical device equipped with an algorithm based on the Born rule, and which purpose is to predict the next events based on the state immediately prior to them, then the system will need the quantum state. The quantum state enables the device to forget all the information about the events that took place before the state of the world immediately prior to the event it aims to make predictions about. The entire history of events is dispensable if we have a defined quantum state. But, conversely, if the device is equipped with a suitable memory, and it keeps track of every single event from the initial state up to the moment in which it is going to predict the next event, its prediction by these means will perfectly match the one made using the quantum state. Eventually, if we condition over many – maybe infinite – collapse events, it might be possible to dispense also of the initial and final conditions (which are still dictated by the quantum state).

As we have seen, as we have seen the violation of λ-mediation can be understood in terms of non-Markovianity. Thus, these results are in line with the common agreement that collapse models with a flash ontology do not satisfy the Markov condition. Remember, in these models, the state at time, let's say, t_4 does not determine by itself the state at t_5. More specifically, the outcome z_4 does not provide the maximal information useful to predict z_5; events previous to z_4 are non trivial in order to calculate our probabilities expectations for event z_5. Once again, this is explained by the fact that z_4 does not screen-off z_5 from $\{z_3, ..., \rho_I\}$. However, if we just put it like that, our characterisation seems to not be time-symmetric: the event z_5, at t_5, depends on the entire history of events from time t_0 to t_5. As we have learned from Price's principle of no temporal double standards, if we do not have a strong reason, then the state at t_5 is determined by its past as well as by its future history. And this is precisely what Leifer and Pusey's theorem aims to show, although in a way in which λ-mediation is satisfied. Thus, having the history of events from the initial to the final state, $\{\rho_I, z_1, ..., z_5, ..., z_{n-1}, \rho_F\}$, we must recognise the fact that the event z_5 depends on both its past and future history. This explains why the dynamics does not recognises a preferred time orientation. The non-Markovianity plus the time symmetry of the models entail that the theory requires non-trivial correlations between future and past events.

The logical consequence of our analysis is, then, that TSCM can satisfy both {PI + PIII}, *and* LPV. Given the violation of LPII, these models can be time-symmetric and no-retrocausal at the same time, without being incompatible with quantum mechanics. Nevertheless, we must highlight that this does not mean that the application of the modified retrocausality theorem to TSCM gives us a trivial and non-interesting result. In fact, although we bypassed the need of retrocausality, if we accept Adlam's argument, we have now a temporally non-local quantum theory. Furthermore, this non-locality across the temporal axis would imply action-at-a-temporal-distance (see 3.3).

Let's conclude this subsection with some remarks about the general research question of this thesis. Given the block universe perspective, enabled by the dynamical time-symmetric structure of TSCM, we might genuinely wonder whether it is conceptually worth to change retrocausality for 'spooky-action-at-a-temporal-distance'. We have that if a quantum theory requires time symmetry in order to be compatible with the block universe perspective, then the theory needs to display either retrocausality or action-at-a-temporal-distance. As we already said, whilst time symmetry (and the block universe perspective) seem to be desirable features of a theory, retrocausality and action-at-a-distance definitely are not equally embraced by the philosophical (and scientific) communities. Thus, although the block universe perspective gives us a natural way to understand the relation between quantum mechanics and special relativity in a way that explains the violations of Bell inequalities through violations of measurement dependence by retrocausal or all-at-once mechanisms, the ontological costs seem to be too high. Nevertheless, in 3.4 we offered a third alternative: time-symmetric quantum theories might exhibit mere temporal global correlations instead of retrocausality or action-at-a-temporal-distance. In the next section, we argue that TSCM exhibit temporal global correlations.

4.5.3 Temporal Global correlations in TSCM

In 3.4 we argued that the rejection of λ-mediation plus the acceptance of time symmetry (be it understood in terms of LPIII or PIII) and no-retrocausality, LPV, entail the existence of temporal global correlations. Our application of the theorem to TSCM reinforces our proposal. This is due to the fact that TSCM are temporally non-local and they are time-symmetric in a way that it is not possible to pick out an absolute time orientation in the set $\{z_i\}$. If we consider again the event z_5, we can appreciate that it is non-trivially correlated with both sets the events $\{z_4, ..., \rho_I\}$ and the events $\{z_{5+1}..., z_{n-1}, \rho_F, \}$. Moreover, the dynamics of the theory does not enable us to identify which set of events happens to take place *earlier than* or *later than* z_5. As we showed, the time direction of the history of events can be swapped and this does not make any difference. For example, it does not matter if we consider ρ_I as the initial state and ρ_F as the final state, or we rather make the transformation $\rho_F \to \rho_I^*$ and $\rho_I \to \rho_F^*$. This transformation leaves invariant every collapse event taking place between the boundary conditions and the joint probability distribution between them.

Taking this into consideration, we are entitled to say that causal concepts do not apply to the set $\{z_i\}$. Remember that, following Myrvold (2016), we adopted a definition of causality in terms of asymmetric relations. Additionally, we pointed out that non-local asymmetric relations can be catalogued as action-at-a-distance, since they can be used to signal. This is not the kind of relation we have found between collapse events in TSCM.

Furthermore, we showed that Leifer and Pusey stated that λ-mediation LPII in the temporal case is an instance of outcome independence. In consequence, a violation of λ-mediation implies that temporal outcome independence is *not* satisfied. Remember that, granting time symmetry, the temporal factorizability condition was derived from measurement independence (which amounts to no-retrocausality LPV), timelike parameter independence (derived from LPV), *and* timelike outcome independence. The modified retrocausality theorem teaches us that if we do not want to reject time symmetry, then we need to choose between giving up one of the factorizability conditions. As we saw, Leifer ad Pusey give up measurement independence in the form of no-retrocausality. Nevertheless, TSCM clearly violate LPII, and then outcome independence. Therefore, at least logically, there is no need to give up measurement independence, and have a retrocausal theory. But then, why do TSCM exhibit mere temporal non-locality rather than action-at-a-temporal-distance?

Analogously to the argument offered by Myrvold (2016), we maintain that giving up outcome independence in the timelike scenario, although it entails temporal non-locality, it should not be interpreted as action-at-a-temporal-distance. A theory that does not meet timelike outcome independence exhibits mere temporal global correlations across histories. Such temporal global correlations do not imply a violation of measurement independence at the fundamental level. For this reason, the temporal global correlations explain why we should not be able to signal towards the future or the past. Moreover, they explain why we cannot recognise a preferred orientation of time: temporal global correlations *are not* asymmetric relations, there is no way to identify what events took place *earlier than* or *later than* others. On the contrary, action-at-a-distance is implied by causal relations, and, in TSCM, collapse events cannot be conceptualised in causal terms.

Someone can still ask why TSCM do no violate LPV. No-retrocausality amounts to the assumption of measurement independence, that is, that the states, λ, are statistically independent of the settings of the measuring device freely chosen by the experimenters. Remember that Leifer and Pusye's theorem is based on the derivation of a temporal Bell inequality which is violated by the predictions of quantum, so that it turns out to be necessary to give up one of the assumptions. A violation of no-retrocausality would make the work in a straightforward way, and, as we said multiple times, it is in fact the alternative suggested by Leifer and Pusey. This perfectly matches the result of Price's toy-model analysis, and naturally, since the theorem is a generalization of his results.

Before concluding our thesis, let's make a few comments regarding why TSCM should not violate measurement Independence and parameter Independence.

First, as Bedingham and Maroney show, GRW with a flash ontology are a special case of TSCM in which the initial state, ρ_I, is the pure state and the final one, ρ_F, is the identity. Standard GRW theories do not violate measurement independence, so we do not see any good reason to believe that TSCM do violate it (see (Bassi and Ghirardi, 2003, sec. 3)).

Second, Price's setup, the retrocausality theorem, and the modified retrocausality theorem are based on the idea that it is not possible to signal in any time direction. In general, the measurement independence condition in the retrocausal context is defined in terms of the changes on our expectation probabilities for λ if we condition on the settings of the measuring devices lying in the future: $P(\lambda|a,b) = P(\lambda)$. We believe that keeping this condition provides a good explanation of why we need to work in the non-signalling sector. Moreover, we are convinced that interpreting TSCM as violating outcome independence (where the outcomes are just the collapse events), but not measurement independence, removes some of the uncomfortable anthropocentrism involved in an explanation that relies in a manipulationalist or interventionist interpretation of retrocausality.

This does not mean necessarily that signalling is not possible in any case. Any condition that allows signalling in a preferred time direction would be emergent and contingent, be it a consequence of an asymmetry between ρ_I and ρ_F or the epistemic asymmetry of an agent. However, the violations of measurement independence would not be fundamental, but emergent and relative to contingent facts. (In theories that posit additional variables, the issue is perhaps different, but we do not need to care about that now).

Bearing these considerations in mind, we can close the section with some comments about our general research question. Do TSCM, which are compatible with the block universe, display characteristics that reconcile quantum mechanics with special relativity? Probably, they do not. This because the key element to have such a reconciliation, by means of the block universe perspective, is a violation of measurement independence. A theory that violates this condition, provides a local explanation of the violation of the spacelike Bell inequalities. However, in this section we argued that TSCM do *not* violate measurement independence, since they exhibit mere temporal global correlations. In consequence, only theories that are retrocausal, and some theories that imply action-at-a-temporal distance (those that involve an 'all-at-once' dynamics) can play such a conciliatory role between quantum mechanics and special relativity.

5 Conclusions

In this thesis, we addressed two questions, a general research question, and a more specific research one. The general research question was concerned with whether the block universe perspective can shed light on the difficulties to reconcile quantum mechanics and the special theory of relativity. Following an argument by McTaggart, we assumed that the block universe required fundamental time-symmetry. This assumption enabled us to analyse whether time-symmetric quantum mechanics had some special characteristics that explain the apparent non-local character usually attributed to quantum theory.

In 2.2 we introduced the spacelike non-locality entailed by orthodox quantum mechanics by means of the EPR argument and Bell's theorem. The contrast between the deterministic and the indeterministic models showed us that non-locality can be understood differently depending on whether we conceive it as consisting of a relation between the parameters and outcomes at two spacelike regions, or only between the outcomes. This leaded us to Myrvold's conception about non-locality which, taking advance of the distinction between parameter and outcome independence, holds that the correlations between parameters and outcomes imply action-at-a-distance whereas the correlations between outcomes and outcomes are mere global correlations. Global correlations cannot be screened-off by a common cause. A relevant element to discriminate between action-at-a-distance and mere global correlations is that the former are asymmetric causal relations, whilst the latter are symmetric, that is, there is no way to determine a temporal priority. The conclusion is that quantum mechanics is non-local, but non-locality does not imply necessarily action-at-a-distance. The relevance of this analysis to our thesis is the following: causal relations between events at spacelike separation entail action-at-a-distance, whereas asymmetric relations between those events can be understood in terms of global correlations. Thus, non-locality does not imply necessarily 'spooky-action-at-a-distance'.

In 3 we explicitly addressed the measurement independence assumption of Bell's theorem, which maintains that the ontic states of the theory are independent of the settings of measurement devices lying in their future light cone. A violation of this condition enables a local explanation of the divergence of quantum mechanics with the spacelike case of Bell inequalities. Thus, measurement independence became crucial.

Price and Leifer and Pusey argue that, given some assumptions, time-symmetric quantum mechanics must violate the measurement independence condition through retrocausal mechanisms. This result is decisive for our general research question: if the block universe requires fundamental time symmetry, then quantum mechanics in the block universe would be reconciled with special relativity since it must be retrocausal, and thus violate measurement independence. An exhaustive analysis of such a reconciliation employing the block universe perspective motivated our research since, we believe that the non-locality of quantum mechanics, and the difficulties it entails concerning the special theory of relativity, had never been directly addressed through an analysis of quantum mechanics in the block universe.

Nevertheless, time-symmetric quantum mechanics does not imply necessarily retrocausality. In 3.3 we presented Adlam's response to the retrocausal arguments. She proposes that time-symmetric quantum mechanics can be understood as violating the Markov condition, in such a way that the theory is temporally non-local. In an 'all-at-once' approach, such temporal non-locality still violates the measurement independence condition 3.4, but in a way that entails 'spooky-action-at-a-temporal-distance'. Thus, even if action-at-a-temporal-distance might restore spacelike non-locality, it still implies temporal non-locality. A question that we did not address in this thesis is whether special relativity prohibits such temporal non-locality, or not.

However, as we learned from Myrvold's analysis of the spacelike case, non-locality does not imply necessarily action-at-a-distance. This means that Adlam's interpretation of time-symmetric quantum mechanics as suggesting temporal non-locality does not need to entail action-at-a-temporal-distance. Temporal non-locality can be understood in terms of global correlations.

The specific research question of this thesis focused on whether time-symmetric quantum mechanics requires retrocausality, action-at-a-temporal-distance or mere temporal global correlations. The answer to this question turns out to be relevant for the general research question since in 3.4 we showed that temporal global correlations do not violate measurement independence. As such, it is dubious whether they enable a reconciliation between quantum mechanics and special relativity.

To provide a concrete defence of our claim that time-symmetric quantum mechanics might exhibit mere temporal global correlations, in 4 we provided a study case. Bedingham and Maroney propose that collapse models (4.2), in specific GRW theory, are time-symmetric if we interpret them with a flash ontology and we set appropriate boundary conditions. This is a novelty since, as we showed in 4.3 the standard interpretation of dynamical collapse models is in terms of a wave-collapse ontology, whose dynamics is generally taken as temporally-asymmetric.

Time-symmetric collapse models are non-Markovian since they dispense of the quantum state. For this reason, they are temporally non-local, and they do not require retrocausality. However, by Adlam's argument, they would imply action-at-a-temporal-distance. Analogously to Myrvold's argument for the spacelike case, we argued that time-symmetric collapse models, although they are temporally non-local, they do not involve action-at-a-temporal distance. The reason is that they violate the timelike case of outcome independence, but parameter independence (which in the timelike context is an instance of measurement independence). Thus, the dynamics of the theory does not enable us to attribute an asymmetry to the beables, which are the flashes or collapse events. Consequently, the history of collapses described by the dynamics cannot be conceptualised in causal terms, since causality is an asymmetric notion. As in the spacelike case, action-at-a-temporal-distance would require a causal relation between parameters and outcomes, which is not shown in the time-symmetric collapse models.

Regarding, the general research question, time-symmetric collapse models are an example of a theory that, although being compatible with the block universe perspective, it does not reconcile quantum mechanics with special relativity. The reason is that they do not imply retrocausality nor action-at-a-temporal-distance, so that they do not violate the measurement independence condition. The temporal global correlations exhibited by the models only violate outcome independence, so they do not shed light on spacelike non-locality.

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